

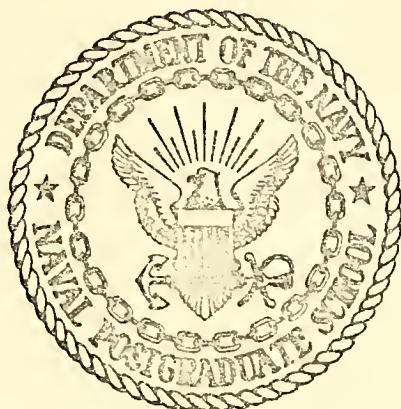
THE IMPLEMENTATION OF A FIXED BASE HELICOPTER
SIMULATION IN THE INVESTIGATION OF
AN AUTOMATIC SCAN SYSTEM

Stephen Sanders Hoxie

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THESIS

THE IMPLEMENTATION OF A FIXED BASE HELICOPTER
SIMULATION IN THE INVESTIGATION OF
AN AUTOMATIC SCAN SYSTEM

by

Stephen Sanders Hoxie

Thesis Advisor:

D.M. Layton

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The Implementation of a Fixed Base Helicopter
Simulation in the Investigation of
an Automatic Scan System

by

Stephen Sanders Hoxie
Lieutenant, United States Navy
B.S., United States Naval Academy, 1966

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ABSTRACT

This report discusses the design and development of a six degree of freedom fixed base simulation of the SH2F helicopter using a hybrid computer interfacing with a computer graphics terminal. The purpose of the simulation was to investigate a scheme for alleviating a helicopter pilot's scan workload during transition to and from hover during instrument flying conditions.

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LIST OF SYMBOLS

g	Acceleration of gravity, ft/sec ²
I_{xx}, I_{yy}, I_{zz}	Moment of inertia about the X,Y,Z body axes respectively, slug ft ²
I_{xz}	Product of inertia = $\int xz dm$, slug ft ²
L, M, N	Applied moments about the X,Y,Z body axes respectively, ft-lbs
m	Mass of the helicopter, slugs
p, q, r	Angular rate of helicopter along the X,Y,Z body axes respectively, radians/sec
u, v, w	Helicopter velocities along the X,Y,Z axes, ft/sec
$v_x^{pt}, v_y^{pt}, v_z^{pt}$	Velocities resolved through ϕ and θ , ft/sec
V_x, V_y, V_z	Inertial velocity of the helicopter along the X,Y,Z axes of the inertial reference frame, ft/sec
X_E, Y_E, Z_E	Position of the helicopter in the inertial reference frame, ft
$\Delta A_{lc}, \Delta B_{lc}$	Lateral and longitudinal cyclic pitch, radians
$\Delta \theta_c$	Collective pitch, radians
$\Delta \theta_R$	Tail rotor collective pitch, radians
ϕ, θ, ψ	Roll, pitch, yaw Euler angles respectively, radians

SUBSCRIPTS

$p, q, r, v, w, B_{lc}, A_{lc}, \theta_c, \theta_R$	Subscripts on X,Y,Z,L,M,N denoting the partial derivatives of the aerodynamic force or moment with respect to $p, q, r, v, w, B_{lc}, A_{lc}, \theta_c, \theta_R$ respectively (i.e. stability derivatives).
A	Subscript on X,Z,M indicating a force or moment due to aerodynamics

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I. INTRODUCTION

The advent of instrument flight in helicopters has been, of necessity, largely developed by the military. Generally speaking, the display of control information has been adapted from that required by fixed-wing aircraft. However, to take full advantage of the helicopter's unique flight capabilities the pilot must be able to control his aircraft with a great deal of precision at low altitudes and low velocities, depending solely on instrument display of the necessary information. Under these conditions conventional pressure sensing instruments are not able to provide information with sufficient accuracy. Technology has solved the problem of the acquisition of precision information with the development of the radar altimeter and Doppler radar systems for the sensing of altitude and velocity information. Current practice is to display this information on additional instruments. Thus, the helicopter pilot is forced to adopt several very different scan patterns of entirely different instruments depending on his flight regime.

During cruising flight and on precision and non-precision instrument approaches, conditions which are essentially the same whether in fixed- or rotating-wing aircraft, the conventional instruments suffice. However, during the critical transition from forward flight to hover, or vice versa, the pilot must transfer his attention to the additional instruments.

Much has been done to determine optimum displays for the approach problem since this can largely be adapted from fixed-wing experience. References 1 through 8 deal with this problem. There is a need for investigation of more suitable means of presenting essential control information during the low speed regimes of transition and hover.

If all of the pertinent information were presented at one location, the pilot could be relieved of much of the problem of shifting his scan to a different set of instruments. The purpose of this project was to evaluate one form of this type of display.

The evaluation was performed by developing first a fixed base simulation, and then the proposed instrumentation scheme. The simulation was developed using a hybrid computer, a graphics computer and a modified Link cockpit simulator. The hybrid is the XDS-9300 digital computer with the COMCOR CI5000 analog computer; this is interfaced with the AGT-10 graphics processor. The cockpit simulator is tied to the computer arrangement by trunklines to the analog computer and by a television camera and repeater to the graphics computer, as shown in Figure 1.

The simulation models the SH2F helicopter, which currently is in use in the Navy's LAMPS program. Because of the author's experience in H-2 helicopters, it was advantageous to conduct the study in this type. Kaman Aerospace Corporation furnished the necessary data for this

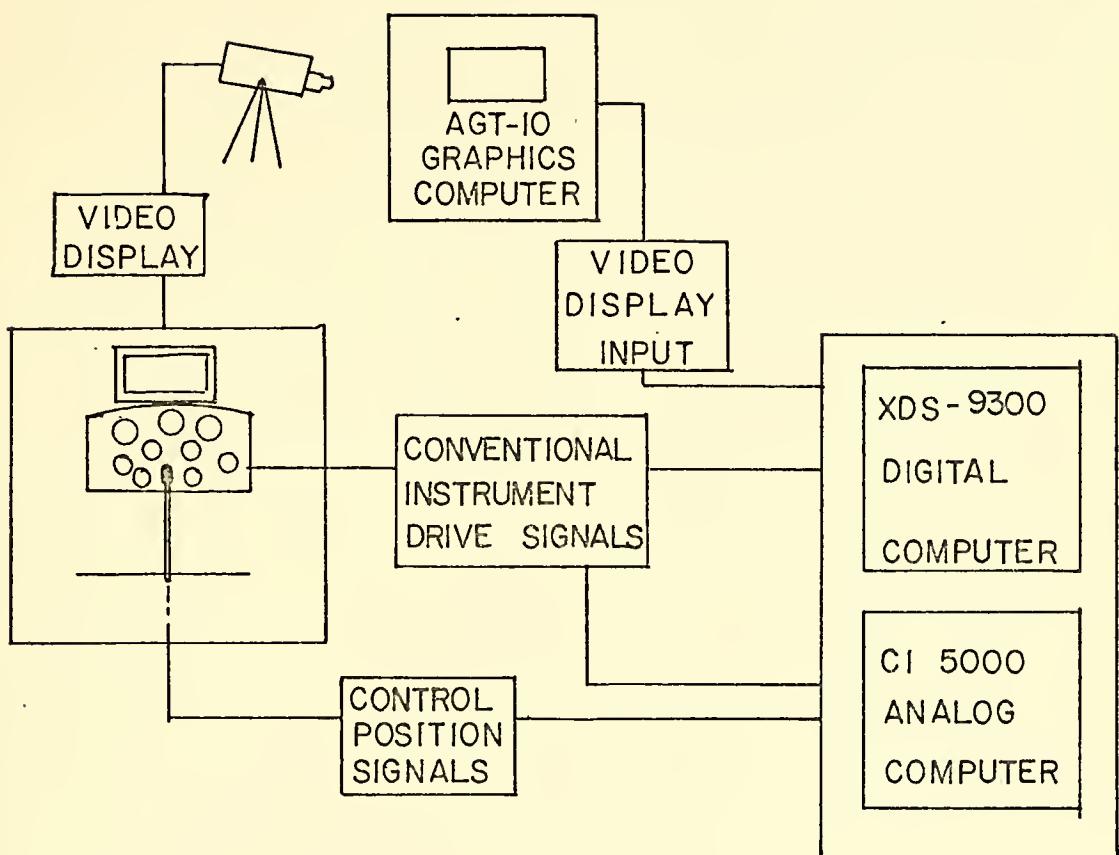


FIGURE 1.

particular model. The simulation includes the automatic stabilization found in the SH2F.

Experienced, instrument-rated helicopter pilots served as evaluation pilots. They were asked to compare the two instrument systems during a simulated instrument flying conditions mission. The pilots were asked to rate each system using the Cooper-Harper Rating System.

II. MISSION

An over-water rescue mission under instrument flying conditions was considered in this study. It was felt that the approach, transition to hover, and precision hovering tasks under night/instrument conditions are the most demanding of a helicopter pilot's skills.

It was assumed that acquisition of the target had already occurred, either by visual sighting by a crewman or some other means. The problem was therefore started with the helicopter three miles downwind at an altitude of 500 feet. The pilot then descended to an altitude of approximately 200 feet; upon reaching 3/4 mile, directions from a crewman were initiated to aid the pilot in transitioning to a hover over the target. After remaining over the target a sufficient length of time to retrieve a survivor, the pilot was to depart straight ahead, climbing out to 500 feet. This concluded the problem.

III. THE SIMULATION

The simulation was accomplished using nonlinear equations of motion in six degrees of freedom. These equations were solved on the analog computer. Control of the simulation system was accomplished through the digital computer; also, certain information required by the analog computer was processed digitally, then converted to the appropriate analog voltage.

The cockpit served as the source of control inputs and the receiving point for information required by the pilot. Hardwired trunklines from the cockpit were patched directly into the analog computer. Each control device, i.e., cyclic stick, collective stick and rudder pedals, was linked to a potentiometer which provided a signal to the analog computer. Appropriate values from the computer solutions were then fed back through the analog to drive the conventional cockpit instrumentation.

When utilizing the Automatic Scan System, the appropriate flight information was fed through the digital computer to the AGT-10 and then by television camera and remote receiver to the cockpit.

The cockpit right hand console contained five switches which paralleled function switches on the analog computer for control of the simulation. These are shown in Figure 2. Once the program had been loaded and the simulator power

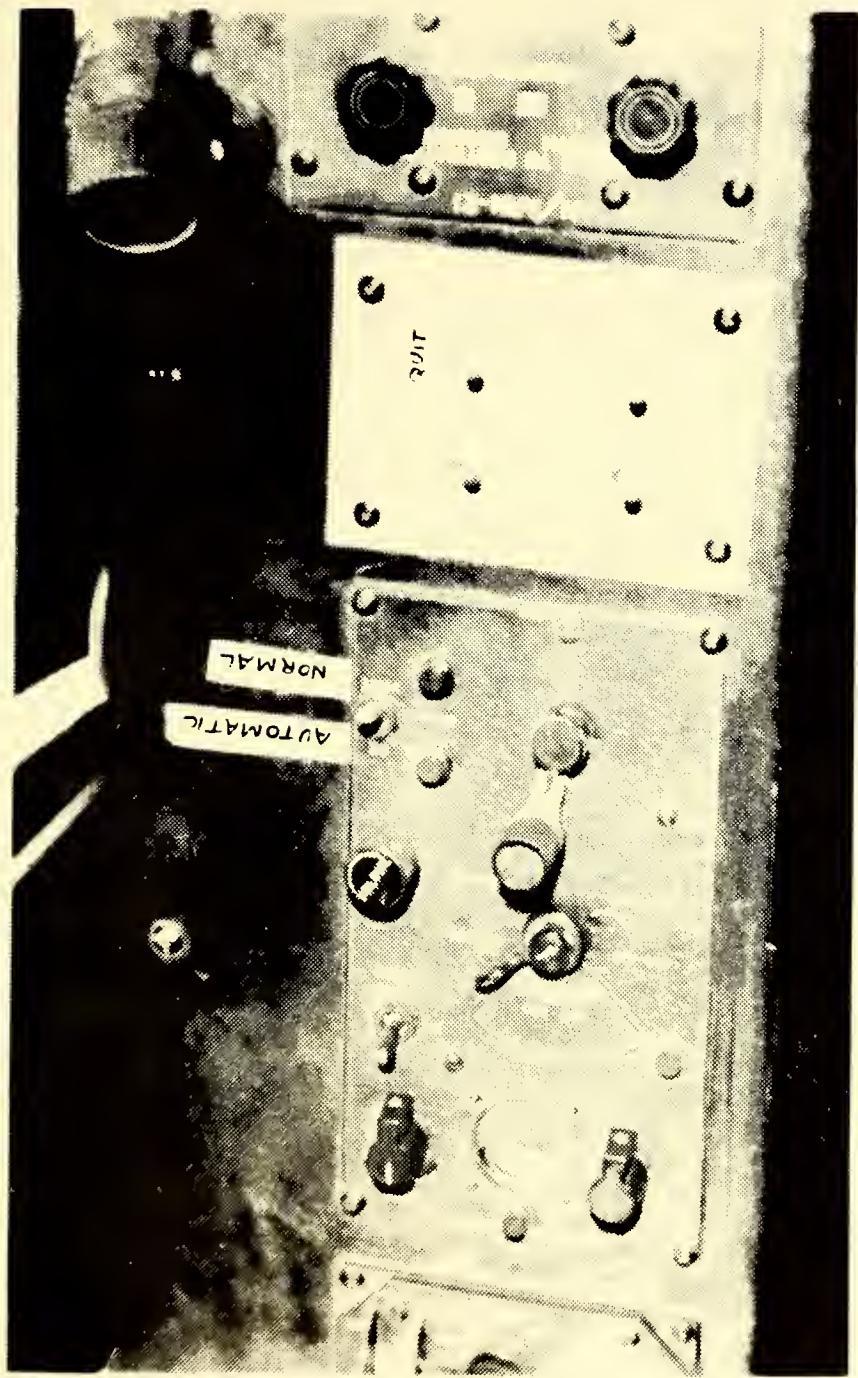


Figure 2. SIMULATION CONTROL PANEL

supplies turned on, placing the FLY switch in the UP position caused the analog to enter the compute mode and start the problem. To stop the problem, the STOP switch was momentarily depressed; then the FLY switch was placed in the down position. At this point the operator could select RERUN which reset the initial conditions or QUIT which terminated the program. The SCAN MODE switch could be positioned to activate the Automatic Scan System when desired.

A. DEVELOPMENT OF EQUATIONS

The nonlinear equations of motion are

$$\dot{u} = rv - qw + \frac{X_A}{m} - g \sin \theta \quad (1)$$

$$\dot{w} = qu - pv + \frac{Z_A}{m} + g \cos \phi \cos \theta \quad (2)$$

$$q = \frac{1}{I_{yy}} m_A \quad (3)$$

$$\dot{v} = pw - ru + \frac{Y_A}{m} + g \sin \phi \cos \theta \quad (4)$$

$$\dot{p} = \frac{I_{xz}}{I_{xx}} \dot{r} + \frac{L_A}{I_{xx}} \quad (5)$$

$$\dot{r} = \frac{I_{xz}}{I_{zz}} \dot{p} + \frac{N_A}{I_{zz}} \quad (6)$$

Equation (1) is taken as an example to show the development of the simulation equations. The remaining simulation

equations were similarly determined. The terms in Equation (1) are straightforward except for X_A , which represents the aerodynamic characteristics of the helicopter. According to Reference 8 it can be assumed, at least approximately, that no coupling exists between the longitudinal and lateral directional motions, due to a plane of symmetry for small perturbations from trimmed flight conditions. The aerodynamic force, X_A , may then be written

$$X_A = X_A(u, q, w, B_{lc}, \theta_c)$$

Therefore,

$$\begin{aligned}
 X_A &= X_A(u_{TR}, q_{TR}, w_{TR}, B_{lc_{TR}}, \theta_{c_{TR}}) \\
 &+ \frac{\partial X_A}{\partial u} (u_{TR}, q_{TR}, w_{TR}, B_{lc_{TR}}, \theta_{c_{TR}}) (u - u_{TR}) \\
 &+ \frac{\partial X_A}{\partial q} (u_{TR}, q_{TR}, w_{TR}, B_{lc_{TR}}, \theta_{c_{TR}}) (q - q_{TR}) \\
 &+ \frac{\partial X_A}{\partial w} (u_{TR}, q_{TR}, w_{TR}, B_{lc_{TR}}, \theta_{c_{TR}}) (w - w_{TR}) \\
 &+ \frac{\partial X_A}{\partial B_{lc}} (u_{TR}, q_{TR}, w_{TR}, B_{lc_{TR}}, \theta_{c_{TR}}) (B_{lc} - B_{lc_{TR}}) \\
 &+ \frac{\partial X_A}{\partial \theta_c} (u_{TR}, q_{TR}, w_{TR}, B_{lc_{TR}}, \theta_{c_{TR}}) (\theta_c - \theta_{c_{TR}}) \quad (7)
 \end{aligned}$$

Thus, the aerodynamic force has been expanded about a steady level flight trim condition whose velocity is that of the

helicopter at that particular instant. Therefore,

$$u_{TR} = u$$

This also requires that

$$q_{TR} = 0$$

$$w_{TR} = w_{TR}(u)$$

$$B_{1c_{TR}} = B_{1c_{TR}}(u)$$

$$\theta_{c_{TR}} = \theta_{c_{TR}}(u)$$

Rewriting,

$$\begin{aligned}
 X_A &= X_A[u, 0, w_{TR}(u), B_{1c_{TR}}(u), \theta_{c_{TR}}(u)] \\
 &+ \frac{\partial X_A}{\partial q} [u, 0, w_{TR}(u), B_{1c_{TR}}(u), \theta_{c_{TR}}(u)](q) \\
 &+ \frac{\partial X_A}{\partial w} [u, 0, w_{TR}(u), B_{1c_{TR}}(u), \theta_{c_{TR}}(u)][w - w_{TR}(u)] \\
 &+ \frac{\partial X_A}{\partial B_{1c}} [u, 0, w_{TR}(u), B_{1c_{TR}}(u), \theta_{c_{TR}}(u)][B_{1c} - B_{1c_{TR}}(u)] \\
 &+ \frac{\partial X_A}{\partial \theta_c} [u, 0, w_{TR}(u), B_{1c_{TR}}(u), \theta_{c_{TR}}(u)][\theta_c - \theta_{c_{TR}}(u)]
 \end{aligned} \tag{8}$$

By dividing by the mass, the stability and control derivatives are obtained as functions of forward speed to give:

$$\begin{aligned}
 \frac{X_A}{m} = & \frac{1}{m} X_A [u, 0, w_{TR}(u), B_{1c_{TR}}(u), \theta_{c_{TR}}(u)] \\
 & + X_q [u, 0, w_{TR}(u), B_{1c_{TR}}(u), \theta_{c_{TR}}(u)](q) \\
 & + X_w [u, 0, w_{TR}(u), B_{1c_{TR}}(u), \theta_{c_{TR}}(u)][w - w_{TR}(u)] \\
 & + X_{B_{1c}} [u, 0, w_{TR}(u), B_{1c_{TR}}(u), \theta_{c_{TR}}(u)][B_{1c} - B_{1c_{TR}}(u)] \\
 & + X_{\theta_c} [u, 0, w_{TR}(u), B_{1c_{TR}}(u), \theta_{c_{TR}}(u)][\theta_c - \theta_{c_{TR}}(u)] \quad (9)
 \end{aligned}$$

These derivatives were readily available from the airframe manufacturer as functions of u . The first term of Equation (9) must be developed by taking its total derivative with respect to forward velocity to obtain:

$$\begin{aligned}
 \frac{dX_A}{du} [u, 0, w_{TR}(u), B_{1c_{TR}}(u), \theta_{c_{TR}}(u)] = & \\
 & + \frac{\partial X_A}{\partial u} [u, 0, w_{TR}(u), B_{1c_{TR}}(u), \theta_{c_{TR}}(u)] \\
 & + \frac{\partial X_A}{\partial w_{TR}} [u, 0, w_{TR}(u), B_{1c_{TR}}(u), \theta_{c_{TR}}(u)] \frac{\partial w_{TR}(u)}{\partial u} \\
 & + \frac{\partial X_A}{\partial B_{1c_{TR}}} [u, 0, w_{TR}(u), B_{1c_{TR}}(u), \theta_{c_{TR}}(u)] \frac{\partial B_{1c_{TR}}(u)}{\partial u} \\
 & + \frac{\partial X_A}{\partial \theta_{c_{TR}}} [u, 0, w_{TR}(u), B_{1c_{TR}}(u), \theta_{c_{TR}}(u)] \frac{\partial \theta_{c_{TR}}(u)}{\partial u} \quad (10)
 \end{aligned}$$

The lead term from equation (10), when divided by the mass, is seen to be

$$x_u = \frac{1}{m} \frac{\partial X_A}{\partial u}$$

However, the remaining partial derivatives are not readily available. For the purpose of the simulation it can be assumed that trim changes with forward velocity are slow and that products of the partials are small compared with X_u . Now the first term in Equation (9) may be obtained by integration.

$$\begin{aligned} \frac{1}{m} X_A [u, 0, w_{TR}(u), B_{1c_{TR}}(u), \theta_{c_{TR}}(u)] &= \\ \int_0^u x_u [u, 0, w_{TR}(u), B_{1c_{TR}}(u), \theta_{c_{TR}}(u)] du \\ + \frac{1}{m} X_A [0, 0, 0, B_{1c_{TR}}(0), \theta_{c_{TR}}(0)] \end{aligned} \quad (11)$$

The last term in Equation (11) is found by substituting into Equation (1) at the hover trim condition. Thus,

$$\frac{1}{m} X_A [0, 0, 0, B_{1c_{TR}}(0), \theta_{c_{TR}}(0)] = g \sin \theta_{TR}(0)$$

$\theta_{TR}(0)$ is known and is a characteristic of the helicopter. Let

$$X_A(0) \equiv g \sin \theta_{TR}(0)$$

In the integral term of Equation (11) X_U is known as a function of U as are the other stability derivatives. Now, by letting

$$X_A(u) \equiv X_u(u) u$$

$$\begin{aligned} \frac{X_A}{m} = & X_A(u) + X_A(0) + X_q(u)q + X_w(u)[w - w_{TR}(u)] \\ & + X_{B_{lc}}(u)[B_{lc} - B_{lc_{TR}}(u)] + X_{\theta_c}(u)[\theta_c - \theta_{c_{TR}}(u)] \end{aligned}$$

For the purpose of this simulation, a great simplification could be made by assuming that changes in many of these airspeed dependent derivatives have only minor effect on the aerodynamic characteristics [Refs. 1 and 11]; these can be held at their hover values. The limited number of digital to analog converters available necessitated this simplification. Additionally, w_{TR} , $\theta_{c_{TR}}$, and $B_{lc_{TR}}$ were held at these hover values [Ref. 1].

Now the X equation may be written as

$$\begin{aligned} \dot{u} = & X_A(u) + X_A(0) + X_q(0)q + X_w(0)w + X_{B_{lc}}(0)[B_{lc} - B_{lc_{TR}}(0)] \\ & + X_{\theta_c}(u)[\theta_c - \theta_{c_{TR}}(0)] - g \sin \theta + rv - qw \quad (12) \end{aligned}$$

Define

$$\Delta B_{lc} \equiv B_{lc} - B_{lc_{TR}}(0)$$

$$\Delta \theta_c \equiv \theta_c - \theta_{c_{TR}}(0)$$

So that

$$\begin{aligned}\dot{u} &= X_A(u) + X_A(0) + X_q(0)q + X_w(0)w + X_{B_{1c}}(0)\Delta B_{1c} \\ &+ X_{\theta_c}(u)\Delta\theta_c - g \sin \theta + rv - qw\end{aligned}\quad (13)$$

Similarly, the remaining equations are determined to be

$$\begin{aligned}\dot{w} &= Z_A(u) + Z_A(0) + Z_q(0)q + Z_w(u)w + Z_{B_{1c}}(u)\Delta B_{1c} \\ &+ Z_{\theta_c}(0)\Delta\theta_c + qu - pv + g \cos \phi \cos \theta\end{aligned}\quad (14)$$

$$\dot{q} = m_A(u) + m_q(0)q + m_w(0)w + m_{B_{1c}}(u)\Delta B_{1c} + m_{\theta_c}(0)\Delta\theta_c \quad (15)$$

$$\dot{v} = Y_v(0)v + Y_p(0)p + Y_r(0)r + Y_{A_{1c}}(0)\Delta A_{1c} + Y_{\theta_R}(0)\Delta\theta_R \quad (16)$$

$$\dot{p} = \frac{I_{xz}}{I_{xx}} \dot{r} + L_p(0)p + L_r(0)r + L_v(u)v + L_{A_{1c}}(0)\Delta A_{1c} + L_{\theta_R}(0)\Delta\theta_R \quad (17)$$

$$\dot{r} = \frac{I_{xz}}{I_{zz}} \dot{p} + N_p(0)p + N_r(0)r + N_v(u)v + N_{A_{1c}}(0)\Delta A_{1c} + N_{\theta_R}(0)\Delta\theta_R \quad (18)$$

The airspeed dependent derivatives are tabulated and then read into the digital computer for use by the analog as necessary.

The stability derivatives furnished by the Kaman Aero-space Corporation in Ref. 9 were calculated with respect to a body-fixed axes system. This system was used in the

simulation and is shown in Figure 3. The derivatives had been calculated for an aircraft in the following configuration:

Gross weight	12577 lb.
Center of gravity at fuselage station	172.5
Main rotor tip speed	691 ft/sec
Sea level standard atmospheric conditions	

After normalizing with respect to mass or the appropriate moment of inertia, most of the derivatives were in a conventional form [Ref. 8] compatible with the equations of motion derived here. Since H-2 type helicopters use a servo-flap system to control cyclic and collective main rotor blade pitch, the main rotor control derivatives were furnished in terms of the servo-flap deflection instead of the rotor blade pitch angle. These derivatives were also presented in a format so that they could be interpreted as control sensitivity or control power in terms of the pilot's control displacements. The flexibility of the simulator cockpit enabled modification at the control system potentiometers to compensate for this difference. In Table I the stability derivatives as used in this simulation are listed; the barred notation (i.e., $\bar{X}_{B_{1c}}$) indicates the modified control derivatives.

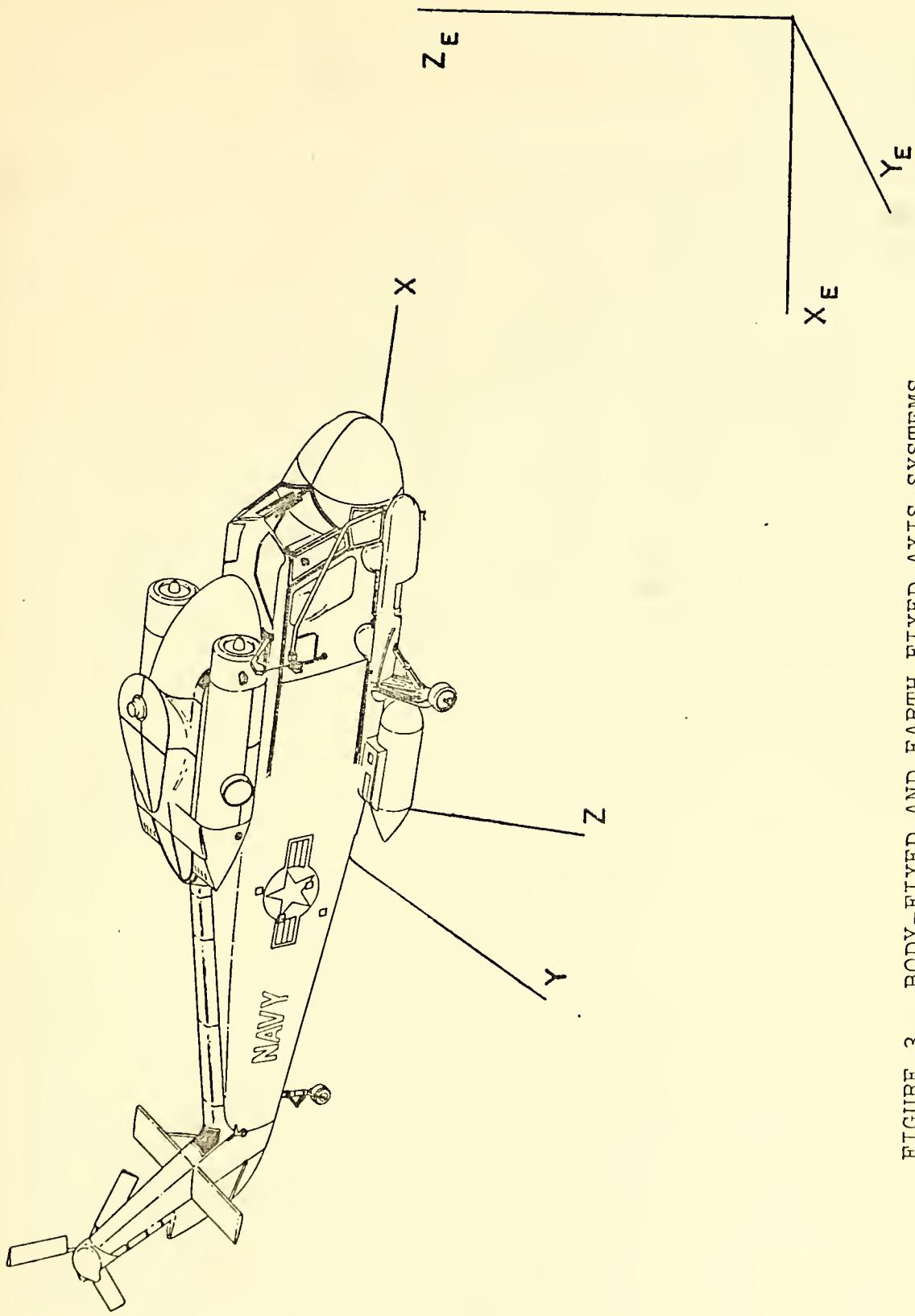


FIGURE 3. BODY-FIXED AND EARTH-FIXED AXIS SYSTEMS

TABLE I
SH2F STABILITY DERIVATIVES AS
USED IN SIMULATION

KTS DERIV.	0	30	50	70	91	112	136
$x_A(u)$	0	.2328	-1.5014	-3.8143	-6.8470	-10.6184	-15.5095
$z_A(u)$	0	-9.2718	-5.8539	.6023	6.5540	18.7617	34.3457
z_w	-.4045	-.5092	-.5843	-.6368	-.6682	-.6875	-.6928
$m_{B_{1c}}$	-12.1694	-12.2229	-12.3438	-12.5480	-12.8240	-13.0365	-12.1535
L_v	-.0215	-.0261	-.0298	-.0352	-.0409	-.0464	-.0519
N_R	-.5871	-.7410	-.8881	-1.0799	-1.2692	-1.4471	-1.6220
N_v	.0172	.0202	.0227	.0272	.0312	.0352	.0399
x_{θ_c}	25.06	22.88	21.96	19.942	17.55	17.617	20.454
$z_{B_{1c}}$	4.5674	35.3516	64.7892	97.4090	131.0581	164.4026	197.3886

DERIVATIVES HELD CONSTANT:

$x_A(0)$	2.8064	y_r	.9627
x_q	.8689	$\bar{y}_{A_{1c}}$	42.6278
x_w	.0491	y_{θ_R}	18.1623
$\bar{x}_{B_{1c}}$	40.129	L_p	-2.4247
$z_A(0)$	-32.077	L_r	.4082
z_q	.5228	$\bar{L}_{A_{1c}}$	36.5078
\bar{z}_{θ_c}	-208.2465	L_{θ_R}	7.0753
m_q	-.7853	N_p	-.0072
m_w	-.0002	$\bar{N}_{A_{1c}}$	1.8767
y_v	-.0338	N_{θ_R}	-11.8578
y_p	1.1390		

B. ANALOG COMPUTER PROGRAM

The CI5000 analog computer served to solve the helicopter's equations of motion and as an interface for signals to and from the cockpit and the digital computer. Additionally it provided appropriate signals to the cockpit instruments. The analog computer was interfaced with the simulator cockpit by 20 trunklines; the use of each is given in Table BI.

Implementation of the helicopter's stability augmentation system was performed on the analog computer.

Control variables for the equations of motion were transmitted directly to the analog from tapped potentiometers in the cockpit. These included potentiometers for longitudinal and lateral cyclic control stick deflections, pedal deflections, and collective stick movements.

Values for airspeed dependent derivatives and functions of Euler angles were obtained from the digital computer for use in the programmed equations of motion.

C. DIGITAL COMPUTER PROGRAM

The digital computer program served to set up the simulator for each run, to determine the correct values for the airspeed dependent derivatives and compute the Euler angles, to determine inertial velocities and position, and to reduce the data generated by each run. Additionally, the digital program furnished information to two non-linear cockpit instruments: the airspeed indicator and the radar altimeter.

Setting up the simulator included reading tables of aerodynamic derivatives and setting the analog potentiometers to the prescribed values. The initial conditions then were set. The program was structured so that after setting the initial conditions it would go through the dynamic loop once to set the derivatives and angular functions properly, then remain in an idle loop until the FLY switch was activated in the cockpit. The initial conditions are listed in Table II.

In the simulation the digital computer received airspeed information from the analog and used a table lookup routine with linear interpolation to determine proper derivative values. These values were then sent to the analog as voltages through digital to analog converters. Computation of the Euler angles was performed using body angular rates obtained through analog to digital converters. Reference 10 provided the following equations.

$$\dot{\theta} = q \cos \phi - r \sin \phi$$

$$\dot{\psi} = q \frac{\sin \phi}{\cos \theta} + r \frac{\cos \phi}{\cos \theta}$$

$$\dot{\phi} = p + \dot{\psi} \sin \theta$$

Integration of these rates was then performed on the analog.

The functions available in the digital computer also made it convenient to determine inertial velocities in that portion of the hybrid. The following equations were used

TABLE II
INITIAL CONDITIONS

U	70 KTS
V	0
W	5.2585 ft/sec.
θ	2.55°
ϕ	0
ψ	0
X_E	18228 ft.
Y_E	0
Z_E	500 ft.
$100\Delta B_{lc}$	1.7687
$200\Delta\theta_c$	-.9034

to resolve the body-fixed velocities through θ and ϕ .

$$v_x^{pt} = u \cos \theta + v \sin \phi \cos \theta + w \cos \phi \sin \theta$$

$$v_y^{pt} = v \cos \phi - w \sin \phi$$

$$v_z^{pt} = -u \sin \theta + v \sin \phi \cos \theta + w \cos \phi \cos \theta$$

The following equations resolved the above velocities through ψ to give the inertial velocities.

$$v_x = v_x^{pt} \cos \psi - v_y^{pt} \sin \psi$$

$$v_y = v_x^{pt} \sin \psi + v_y^{pt} \cos \psi$$

$$v_z = v_z^{pt}$$

The v_x and v_y equations were integrated digitally to provide inertial position information. The v_z equation was integrated on the analog to provide height information for the altimeters.

Generation of the data necessary for the graphics computer presentation was also done in the digital computer. This consisted of three major sections. For the conventional instrumentation system, use of a direction velocity indicator was required. This instrument was implemented by portraying it on the graphics computer then relaying it to the cockpit television repeater. This required two sections of data, one for the "fixed" picture of the instrument outline and

velocity graduations, the other to generate the "moving" indicators. As depicted, the graphics picture closely resembled the actual instrument as shown in Reference 11. The third section of data for the graphics computer was that necessary to create the Automatic Scan System display. For both systems the display of text to simulate directions from a crewman was controlled digitally.

The digital program also furnished control of the coordinated turn system.

D. COCKPIT

The cockpit used was basically the Link Aviation, Inc., Type C-II instrument trainer with modifications as reported in Reference 12. To make the cockpit suitable for helicopter simulation, it was necessary to perform further modifications.

The conventional throttle was deactivated, and a collective control stick added to the left console adjacent to the pilot's seat. This control stick was constructed from a spare throttle assembly rotated approximately ninety degrees so that the conventional fore and aft motion becomes up and down. The short length of the stick, as compared to those in use in actual helicopters, resulted in much more noticeable curvature of the stick's motion when moved to full deflection. However, during a normal evaluation the flight collective stick movements were small enough to prevent this from being significant to the pilot. The collective stick is depicted in Figure 4.



FIGURE 4. COLLECTIVE CONTROL STICK INSTALLATION

Conventional instruments necessary for this mission were airspeed indicator, remote attitude indicator, radar altimeter, altimeter, compass, needle/ball, vertical speed indicator, and directional velocity indicator (DVI). The instruments were arranged as shown in Figure 5. This closely represented the instrument layout used in H-2 type helicopters; differences were due to the physical limitations of the instrument panel and the types of instruments available for use in the simulator. Figure 6 shows the flight instrument arrangement of a typical H-2 helicopter.

Since there was no suitable indicator available, one instrument, the DVI, was depicted graphically on the AGT-10 and relayed to the television repeater in the cockpit. This instrument was used to present velocity information during transition and hover. A horizontal cross pointer indicated forward velocity while sideward velocities were indicated by a vertical cross pointer; vertical velocity was indicated by a pointer on the left side of the indicator. The instrument was configured so that when the helicopter was in a hover with no velocity, the cross pointers were centered. The DVI is shown for various conditions in Figures 7 and 8. The fixed portion of the instrument, including the outline and the indicator graduations, was generated by the main program as the initial conditions were set. The moving presentation, including vertical speed indication and vertical and horizontal cross pointers, was then superimposed on the fixed picture. These indicators were then updated in a

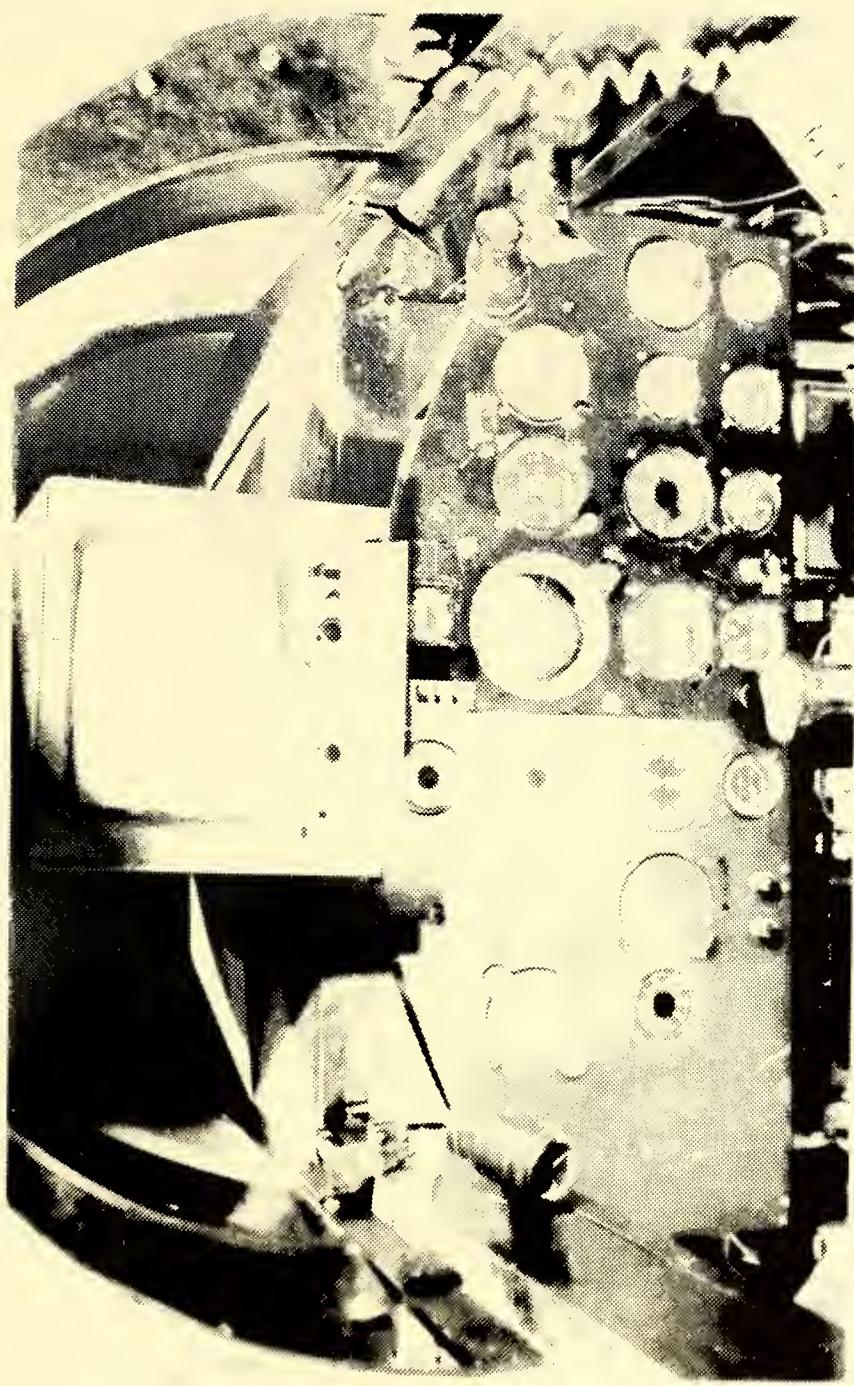
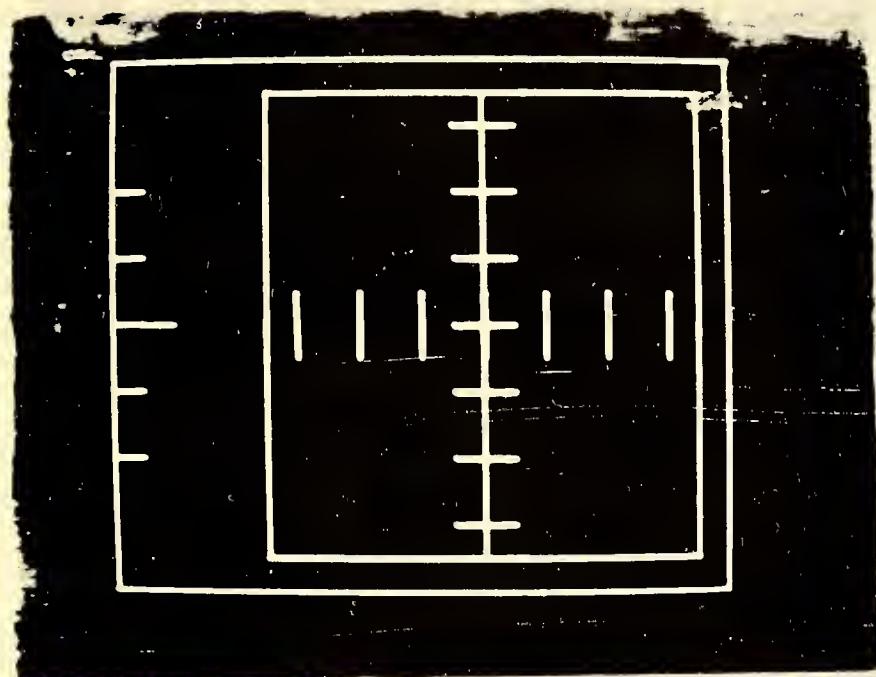


FIGURE 5. SIMULATOR INSTRUMENT PANEL ARRANGEMENT



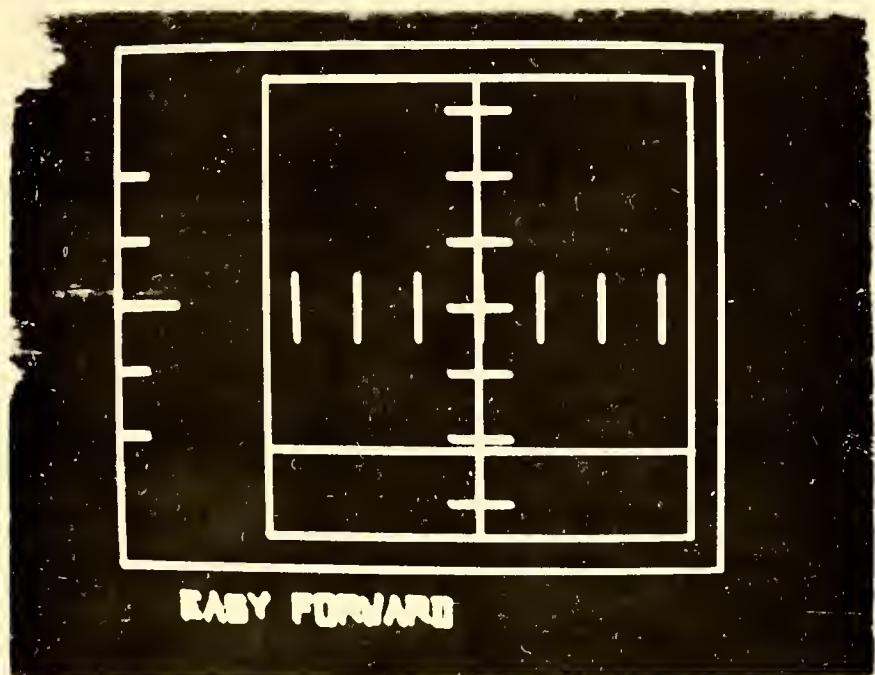
TYPICAL H-2 INSTRUMENT PANEL

FIGURE 6

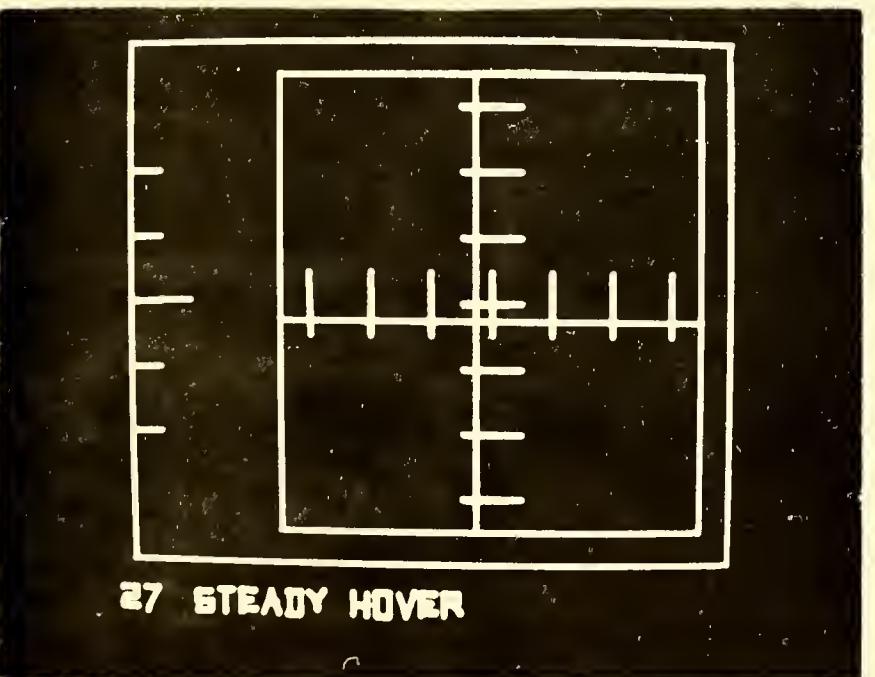


DIRECTION VELOCITY INDICATOR IN
CRUISE CONDITION

FIGURE 7



BABY FORWARD



27 STEADY HOVER

DIRECTION VELOCITY INDICATOR
AND CREW DIRECTIONS

FIGURE 8

subroutine each time the digital program went through its dynamic loop.

When flying a mission of this nature a helicopter pilot is usually assisted through voice communications by a crewman for precise position and velocity control during the final stages of the approach and in a hover. To simulate these directions, standardized phrases were portrayed on the graphics terminal for relay to the cockpit repeater. Introduction of the phrases was keyed to the helicopter's distance from the target; the first directions given when the helicopter came within approximately three-quarters of a mile. A listing of the phrases is given in Table III; their display is depicted in Figure 8.

Of the remaining instruments, the airspeed indicator, the radar altimeter, and the vertical speed indicator were DC meter movements driven through the trunklines from the analog computer. The airspeed indicator and radar altimeter had nonlinear presentations to the pilot; this necessitated logic in the digital program for control of these instruments.

The information presented by the airspeed indicator was derived from u , the forward velocity component in the body-fixed axis system. The radar altimeter showed the distance to the surface for altitudes below 200 feet.

The altimeter and gyro bank and pitch systems were configured as reported in Ref. 12. The needle-ball remained as configured in Ref. 13. The compass system (RMI) was not

TABLE III
CREW DIRECTIONS

STEADY FORWARD	XE < 3/4 MILE
EASY FORWARD	XE < 1500 FT.
STOP EASY FORWARD, STEADY HOVER	XE < 100 FT.
EASY BACK	XE < -50 FT.
STOP EASY BACK, STEADY HOVER	XE < -40 FT.
EASY RIGHT	YE < -100 FT.
STOP EASY RIGHT, STEADY HOVER	YE < -40 FT.
EASY LEFT	YE > 100 FT.
STOP EASY LEFT, EASY HOVER	YE > 40 FT.
STEADY HOVER	$-40 \leq XE \leq 40$ $-40 \leq YE \leq 40$
MAN ON HOIST	HOVER TIME > 30 SEC.
MAN IN AIRCRAFT	HOVER TIME > 45 SEC.
COME UP YOU ARE LOW	ZE < 10 FT.

activated due to difficulty in obtaining repeatable readings for a given input with the available instrument.

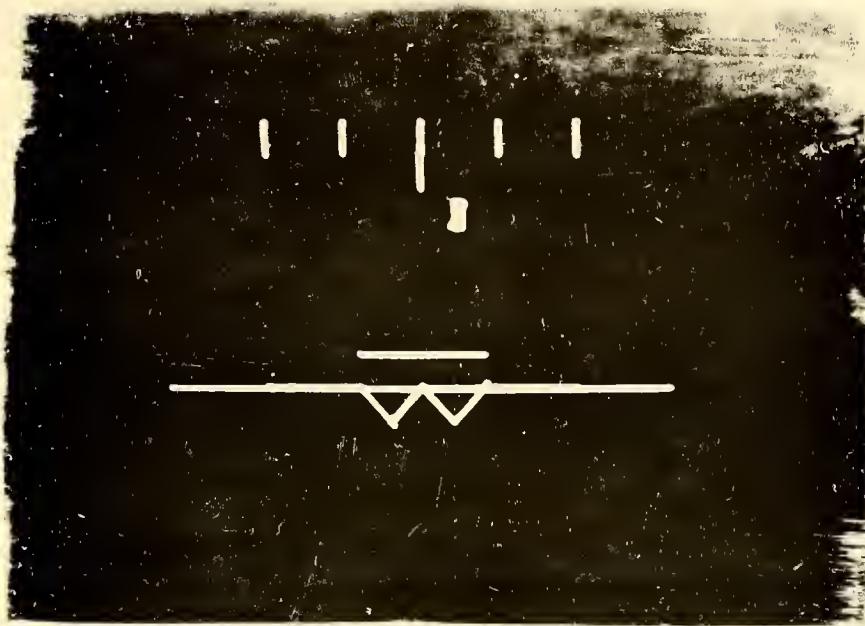
As in H-2 type helicopters, the thumb button on the left side of the cyclic control stick was used for control of the coordinated turn system. Depressing this button allowed the helicopter to turn in balanced flight without the requirement for rudder pedal inputs. Normal turns using the rudder pedals were also possible. When neither the coordinated turn button was depressed nor the rudder pedals deflected, sufficient feedback was incorporated to insure that heading was maintained: the "heading hold" feature of H-2 type helicopters. When either type of turn was indicated, the heading hold was released, allowing the helicopter to turn. Control of this system was accomplished through the digital program and the logic board of the CI 5000.

IV. AUTOMATIC SCAN SYSTEM

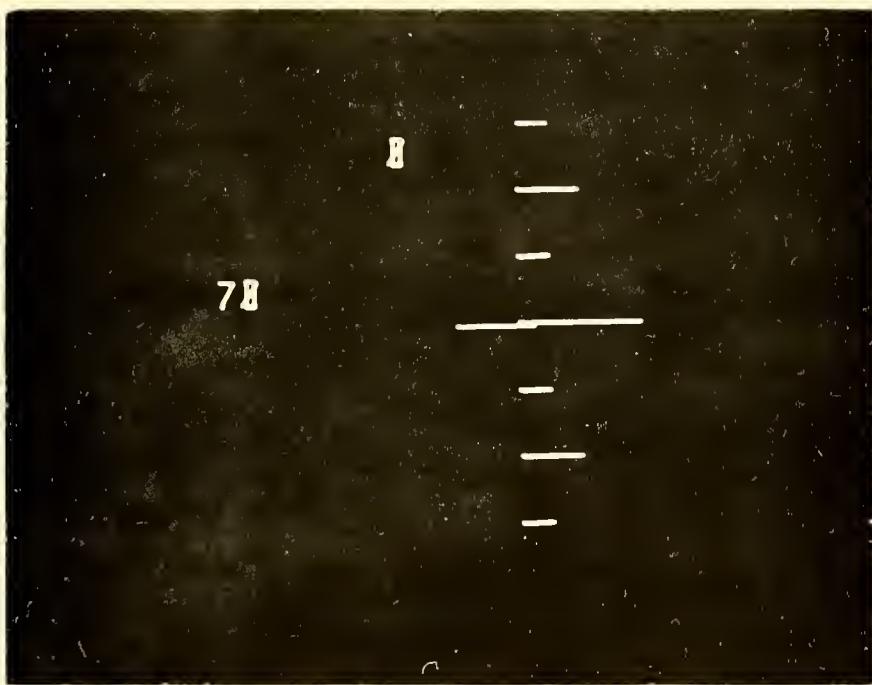
The Automatic Scan System was designed to replace the conventional instrument display. When using this system, all necessary information for instrument flight was presented on the television repeater in the cockpit except the needle/ball; for this instrument only, the pilot could refer to his normal instrumentation.

Flight control information was presented sequentially on the repeater; first an attitude display was depicted, then airspeed, and finally altitude, before the sequence was initiated again. The attitude display resembled a conventional attitude indicator with artificial horizon, miniature airplane and angle of bank indicator. Depiction of airspeed information was done digitally to show the helicopter's airspeed, with indices and a moving pointer to show the direction and rate of change. Altitude information was presented similarly with a digital readout for height above the surface and a scale pointer to show vertical speed. Heading was also provided digitally with an arrow pointing to the appropriate direction during turns. The attitude and airspeed presentations are shown in Figure 9. In the photographs the heading readout is shown just above the turn arrow. The altitude display is shown in Figure 10(a).

If the helicopter airspeed was less than 35 knots, then a display similar to the DVI of the conventional system appeared in place of the airspeed presentation. This DVI

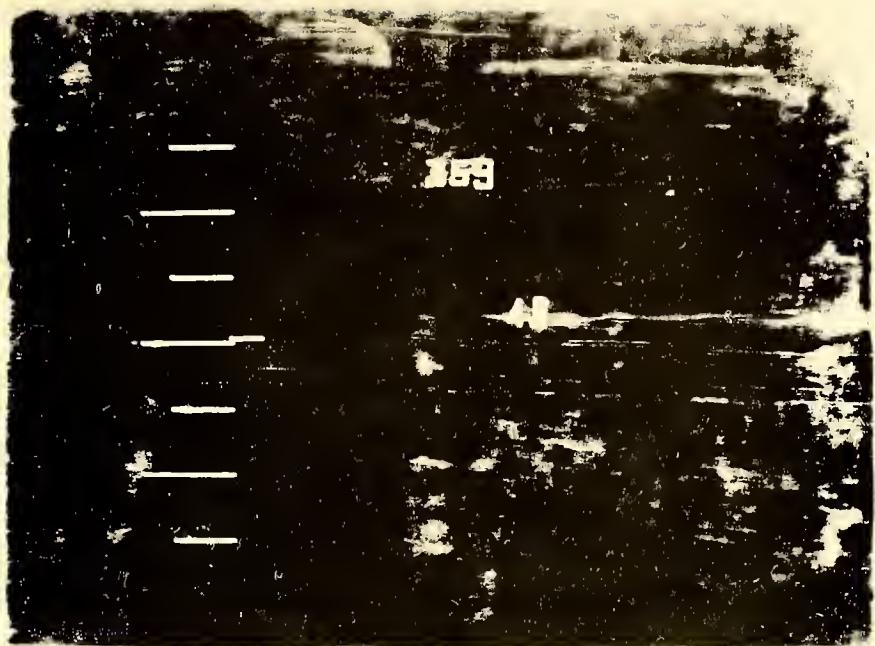


(a) ATTITUDE INDICATION

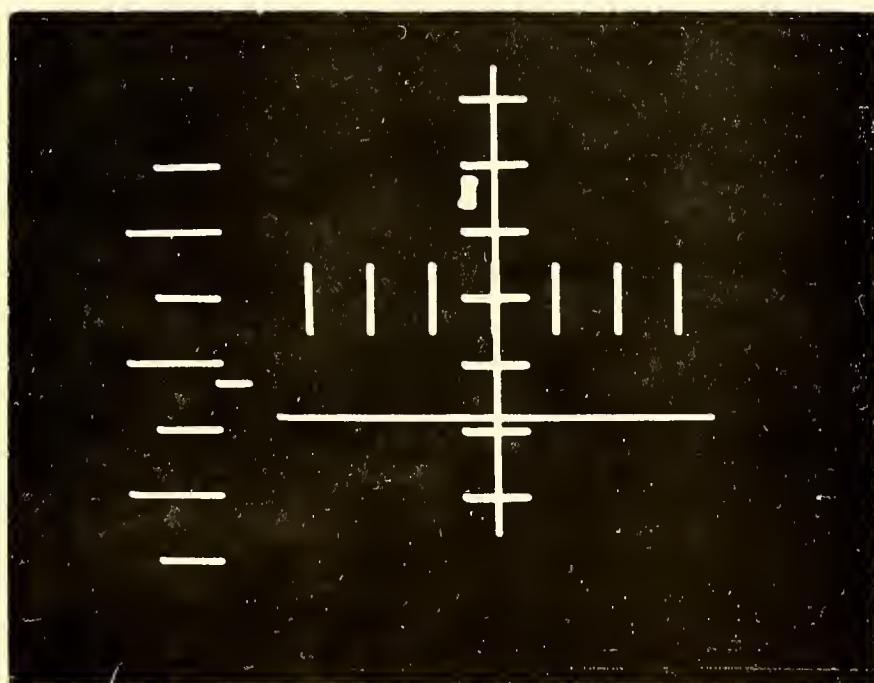


(b) AIRSPEED INDICATION

FIGURE 9



(a) ALTITUDE INDICATION



(b) DIRECTION VELOCITY INDICATION

FIGURE 10

display incorporated a vertical speed indicator identical to that of the altitude display, which followed the DVI in the sequence. Thus, the pilot was presented with critical altitude rate information for twice as long when he needed it most. The DVI is shown in a near hover flight condition in Figure 10(b).

Each of these presentations was depicted for two seconds. A pilot could assimilate the information at a faster rate, but initiating a corrective control movement proved to be difficult. A longer interval proved detrimental to adequate control because of excessive time between presentations of a given display. With an interval of two seconds, a pilot waited four seconds before he saw the same display again. In transition and hover, however, the DVI increased the visibility of altitude information to four seconds, so that the pilot was without this essential display for only two seconds.

V. EVALUATION

Five experienced Navy helicopter pilots were utilized to evaluate the simulator and the Automatic Scan System. One pilot, subject E, was a graduate of Navy Test Pilot School. Each subject was given sufficient time to acquaint himself with the simulator and gain some proficiency using the conventional instrumentation system. Stripchart recordings were then made of U, V, VZ and ZE during transition and hover over the target. At this time, each pilot was asked to subjectively rate the simulator's characteristics using the Cooper-Harper Scale shown in Figure 11. As well as providing rating of the basic simulator, this furnished each pilot with a baseline with which to evaluate the Automatic Scan System.

Each pilot was then introduced to the Automatic Scan System and allowed to practice using it until he felt comfortable with it. Recordings were again made during the transition and hover phases of the mission. Upon completion, the pilot was asked to rate the Automatic Scan System.

Table IV lists the experience level of each pilot and shows his rating of the basic simulator and the Automatic Scan System.

As seen in Table IV, the Cooper-Harper ratings given to the basic simulator generally show its characteristics to be satisfactory. In comments elicited from the pilots, the major complaints concerned the lack of proper cyclic control

HANDLING QUALITIES RATING SCALE

ADEQUACY FOR SELECTED TASK OR
REQUIRED OPERATION*

AIRCRAFT
CHARACTERISTICS DEMANDS ON THE PILOT
IN SELECTED TASK OR REQUIRED OPERATION* PILOT
RATING

Excellent Highly desirable	1	Pilot compensation not a factor for desired performance
Good Negligible deficiencies	2	Pilot compensation not a factor for desired performance
Fair — Some mildly unpleasant deficiencies	3	Minimal pilot compensation required for desired performance

Minor but annoying deficiencies	4	Desired performance requires moderate pilot compensation
Moderately objectionable. deficiencies	5	Adequate performance requires considerable pilot compensation
Very objectionable but tolerable deficiencies	6	Adequate performance requires extensive pilot compensation

Major deficiencies	7	Adequate performance not attainable with maximum tolerable pilot compensation. Controllability not in question
Major deficiencies	8	Considerable pilot compensation is required for control
Major deficiencies	9	Intense pilot compensation is required to retain control

Major deficiencies	10	Control will be lost during some portion of required operation
--------------------	----	---

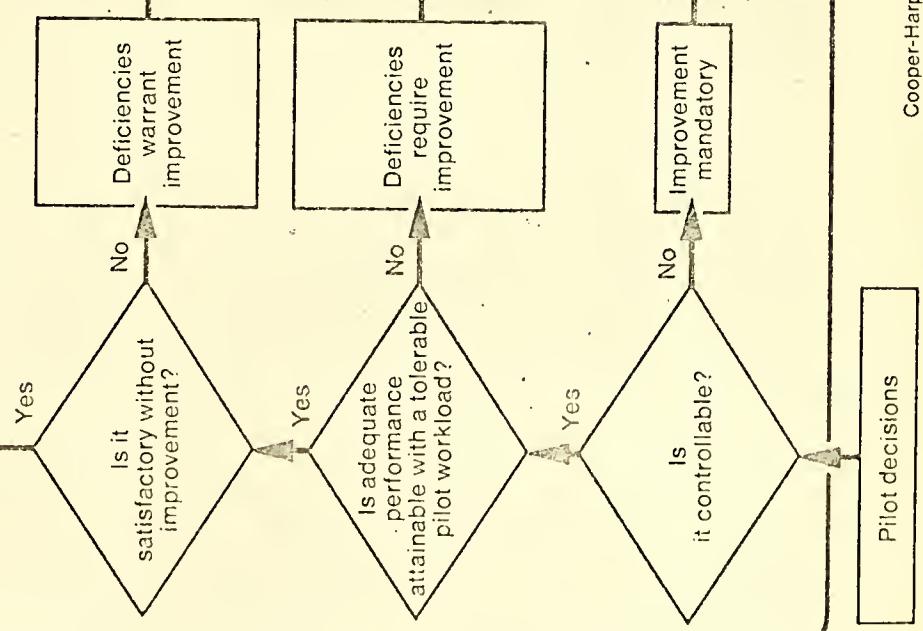


FIGURE 11

* Definition of required operation involves designation of flight phase and/or subphases with accompanying conditions.

TABLE IV
PILOT EXPERIENCE AND RATINGS

PILOT	TOTAL TIME	INSTRUMENT TIME	BASIC SIMULATOR	AUTOMATIC SYSTEM
A +	3800	600	4	5
B	1450	300	3	8
C	1200	300	4	6
D	1200	125	3	4
E + *	4000	900	3	5

* Graduate Navy Test Pilot School

+ Special instrument card

control feel and the insensitivity of the cyclic trim system. These were properties of the Link cockpit and could not be altered without reducing the flexibility of the equipment for other projects.

Ratings given by the project pilots to the Automatic Scan System were somewhat less than satisfactory. In all cases it was felt that improvement was necessary. The subjects felt that the information displayed was not available long enough to take adequate corrective action, and there was not enough time after perceiving an error to see the results of the correction. Additionally, they felt that the time until the same display appeared again (i.e., 4 seconds) was excessive. These deficiencies were due to the pilot not being able to view selectively a particular display when he felt he needed it; instead he had to wait until the desired information was available again.

VI. CONCLUSIONS

As a result of the evaluation of the simulator and the Automatic Scan System, the following conclusions were reached:

- (1) The basic simulator adequately represents the SH2F helicopter and therefore can be used in further research involving this type.
- (2) The Automatic Scan System as configured here, appearing in a fixed sequence, is not capable of supplying adequate flight control information to the pilot.
- (3) The pilot needs to be able to select for himself that information which he deems necessary. This warrants the further investigation of integrated displays to alleviate the pilots scan problem during transition to and from hover.

Additionally, the flexibility inherent in the hybrid computer-based simulator allows it to be readily adapted to innumerable further projects. Obviously, more research in integrated displays could be done. Also a three-dimensional perspective could be generated in the graphics computer to allow a representation of what the pilot sees out the windshield. This would be useful, for instance, in evaluating night landing aids for employment aboard ships carrying LAMPS helicopters.

APPENDIX A

The Digital Program

A listing of the Fortran computer program is contained within this appendix. It includes the main program, the FLY subroutine, which forms the dynamic loop, and three subroutines.


```

* SIX DEGREE OF FREEDOM HELICOPTER SIMULATION
*
* REAL MNW, MBCU, LVU, NRU, NVU, MAIC, MNWUC, MBUC, LVUC, NRUC, NVUC, MQO, MTHCO,
1 LPOL, LACO, LARO, NPO, NALO, NARO, MAI
  DIMENSION ITD(15), IGD(8)
  CMMN/DERIVA/XAI(7), ZAI(7), MAI(7), ZWU(7), MBCU(7), LVU(7), NRU(7),
1 NVU(7), XTHU(7), ZBIU(7)
  CMMN/STATE/VELB(3), ANGRAT(3), ANGLE(3), POSIT(3)
CMMN IDEV
CMMN X(120), Y(120), Z(120)
CMMN ITALK(9,14), IDVI(60), IND(20)
  DIMENSION XY(120,2), JXY(2)
NAMELIST IDEV
EQUIVALENCE ((X(1),XY(1,1)),(Y(1),XY(1,2)),
EQUIVALENCE (VELB(1),U),(VELB(2),V),(VELB(3),W),(ANGRAT(1),P),
1 (ANGRAT(2),Q),(ANGRAT(3),R),(ANGLE(1),THETA),(ANGLE(2),PSI),
1 (ANGLE(3),PHI),(POSIT(1),XE),(POSIT(2),YE),(POSIT(3),ZE)
*
* READ AERODYNAMIC DERIVATIVE TABLE
*
* READ(5,1)(XAI(I),I=1,7)
  READ(5,1)(ZAI(I),I=1,7)
  READ(5,1)(MAI(I),I=1,7)
  READ(5,1)(ZWU(I),I=1,7)
  READ(5,1)(MBCU(I),I=1,7)
  READ(5,1)(LVU(I),I=1,7)
  READ(5,1)(NRU(I),I=1,7)
  READ(5,1)(NVU(I),I=1,7)
  READ(5,1)(XTHU(I),I=1,7)
  READ(5,1)(ZBIU(I),I=1,7)
  FORMAT(7F10.4)

```


PRINT DERIVATIVE TABLE

```

* **** PRINT DERIVATIVE TABLE ****
* **** WRITE (6,3)
* 3   FORMAT('1',40X,'AIRSPEED DEPENDENT DERIVATIVES',//)
* **** WRITE (6,4)
* 4   FORMAT('0',25X,'0',10X,'30',8X,'50',10X,'70',10X,'91',9X,'112',110X,'136',//)
* **** WRITE (6,5)(XAI(I),I=1,7)
* **** WRITE (6,6)(ZAI(I),I=1,7)
* **** WRITE (6,7)(MAI(I),I=1,7)
* **** WRITE (6,8)(ZAU(I),I=1,7)
* **** WRITE (6,10)(MBCU(I),I=1,7)
* **** WRITE (6,11)(LVU(I),I=1,7)
* **** WRITE (6,12)(NRU(I),I=1,7)
* **** WRITE (6,13)(NVU(I),I=1,7)
* **** WRITE (6,15)(XTHU(I),I=1,7)
* **** WRITE (6,17)(ZBIU(I),I=1,7)
* 5   FORMAT('0',2X,'XAI',10X,7F12.4,/)
* 6   FORMAT('0',2X,'ZAI',10X,7F12.4,/)
* 7   FORMAT('0',2X,'MAI',10X,7F12.4,/)
* 8   FORMAT('0',2X,'ZWU',10X,7F12.4,/)
* 10  FORMAT('0',2X,'MBICU',8X,7F12.4,/)
* 11  FORMAT('0',2X,'LVU',10X,7F12.4,/)
* 12  FORMAT('0',2X,'NRU',10X,7F12.4,/)
* 13  FORMAT('0',2X,'NVU',10X,7F12.4,/)
* 16  FORMAT('0',2X,'XTHU',10X,7F12.4,/)
* 17  FORMAT('0',2X,'ZBIU',10X,7F12.4,/)
* **** READ(5,901)((ITALK(I,J),I=1,9),J=1,14)
* 901 FORMAT(9A4)
* **** WRITE(6,902)
* 903 FORMAT('0',40X,'CREW DIRECTIONS',//)
* **** WRITE(6,902)((ITALK(I,J),I=1,9),J=1,14)
* 902 FORMAT(40X,9A4)
* **** SET POTENTIOMETERS TO ASSIGNED VALUES
* ****

```



```

***** CALL SETP8T (4HP0000,0890,4HP001,4724,4HP002,1320,4HP003,2006,4HP004
1,0869,4HP005,1962,4HP006,0800,4HP007,0000,4HP010,0100,4HP011,1224,
14HP012,25000,4HP013,1250,4HP014,0100,4HP015,0838,4HP016,0250,4HP017
1,7075,4HP020,7553,4HP021,0389,4HP022,1066,4HP023,0241,4HP024,2000,
14HP025,5000,4HP026,0285,4HP027,0845,4HP030,4000,4HP031,1816,4HP032
1,9127,4HP033,1021,4HP034,6062,4HP035,2598,4HP036,4000,4HP037,2500,
14HP040,1093,4HP041,0018,4HP042,4692,4HP043,1186,4HP044,4000,4HP045
1,1250,4HP046,6250,4HP047,2500,4HP050,3200,4HP051,1041,4HP052,2000,
14HP053,1046,4HP054,1052,4HP055,6282,4HP056,5000,4HP057,0000)
30 INPUT(101)
***** SET INITIAL CONDITIONS
20 CALL INCND
    IL=0
    IR=0
    MARK=0
***** INITIALIZE THE GRAPHICS COMPUTER
    CALL DTINIT (IDEV, ITD, 15, IER)
    CALL DGINIT (IDEV, IGD, 6, IER)
    IF (IER.NE.0) OUTPUT(6) IER, 'DTINIT'; GO TO 30
    IF (TEST(6).LT.0) G9 T8 50
    IDVI(1)=IHEAD(0,10)
    IDVI(2)=IPACK(-1,0,1,0,0)
    IDVI(3)=IPACK(1,0,1,0,1)
    IDVI(4)=IPACK(1,0,0,6,1)
    IDVI(5)=IPACK(-1,0,0,6,1)
    IDVI(6)=IPACK(-1,0,1,0,1)
    IDVI(7)=IPACK(-5,0,9,0)
    IDVI(8)=IPACK(0,9,0,9,1)
    IDVI(9)=IPACK(0,9,0,5,1)
    IDVI(10)=IPACK(-5,0,5,1)

```



```

1 DVI(11)=IPACK((-•5,•9,1)
1 DVI(12)=IPACK((-1•,•6,0)
M=0
YL=•6
D9 40 K=1,5
1 DVI(13+M)=IPACK((-•9,YL,1)
1 DVI(14+M)=IPACK((-1•,YL-•2,0)
M=•+2
YL=YL-•2
CONTINUE
1 DVI(23)=IPACK(.•1,•8,0)
M=0
YL=•8
D9 41 K=1,7
1 DVI(24+M)=IPACK(.•3,YL,1)
1 DVI(25+M)=IPACK(.•1,YL-•2,0)
M=•+2
YL=YL-•2
CONTINUE
1 DVI(38)=IPACK(-•4,•3,0)
M=0
XL=-•4
D9 42 K=1,7
1 DVI(39+M)=IPACK(XL,•1,1)
1 DVI(40+M)=IPACK(XL+•2,•3,0)
M=•+2
XL=XL+•2
CONTINUE
1 DVI(53)=0
1 DVI(54)=0
CALL GRAPH0(IDEV, IDVI, 54, 1, IER
***** NOW START T6 FLY ****
***** CALL FLY(LL, IR, MARK) ****
42

```



```
CALL HOLD
22  IF (TEST(5).LT.0.)G9 T8 20
     IF (TEST(4).LT.0.) G8 T8 21
     G9 T8 22
     CALL P0TSET
     STOP
21  END
```



```
SUBROUTINE INC9ND
C99999/STATE/VELB(3),ANGRAT(3),ANGLE(3),POSIT(3)
DC 1  I=1,3
VELB(1)=0.0
DS 2  I=1,3
      ANGRAT(1)=0.0
      ANGLE(1)=2.55/57.3
      ANGLE(2)=0.0
      ANGLE(3)=0.0
      POSIT(1)=3.*6076.
      POSIT(2)=0.0
      POSIT(3)=500.
      RETURN
END
```

1 2


```

SUBROUTINE FLY(11,IR,MARK)
INTEGER DTNEW,DTOLD
REAL MWU,MBCU,LVU,NRU,NVU,MQO,MTHCO,LPO,LACO,LARO,NPO,NALO,NAR
10,MAIC,MWUC,MBUC,LVUC,NRUC,NVUC,MAI
CMMN/DERIVA/XAI(7),ZAI(7),MAI(7),ZWU(7),MBCU(7),LVU(7),NRU(7),
1NVU(7),XTHU(7),ZBIU(7)
CMMN/STATE/VELB(3),ANGRAT(3),ANGLE(3),POSIT(3)
CMMN IDEV
CMMN X(120),Y(120),Z(120)
CMMN ITALK(9,14),IDVI(60),IND(20)
EQUIVALENCE (VELB(1),U),(VELB(2),V),(VELB(3),W),(ANGRAT(1),P),
1(ANGRAT(2),Q),(ANGRAT(3),R),(ANGLE(1),THETA),(ANGLE(2),PSI),
1(ANGLE(3),PHI),(POSIT(1),XE),(POSIT(2),YE),(POSIT(3),ZE)
THETIC=THETA
CALL RESET(1000)
CALL HSLD
DTOLD=0.0
IFLAG=0
TIME=10.
I=1
CALL WRITECLK(0)
S9 T8 100
1F (IFLAG.EQ.1) GO TO 100
CALL COMPUTE
CALL STARTCLK
IFLAG=1
***** GET VALUES OF AERODYNAMIC DERIVATIVES FROM TABLE ****
* 99 CALL LOOKUP (XAI,U,C)
* 100 CALL ADK (2,U4)
U=250.*U4
CALL LOOKUP (ZAI,U,C)
XAIC=C
CALL LOOKUP (ZAI,U,C)
ZAIC=C

```



```

CALL LOOKUP (MA1,U,C)
MA1C=C
CALL LOOKUP (ZWU,U,C)
ZWUC=C
CALL LOOKUP (MBCU,U,C)
NBUC=C
CALL LOOKUP (LVU,U,C)
LVUC=C
CALL LOOKUP (NRU,U,C)
NRUC=C
CALL LOOKUP (NVU,U,C)
NVUC=C
CALL LOOKUP (XTHU,U,C)
XTHUC=C
CALL LOOKUP (ZBIU,U,C)
ZBIUC=C
***** DETERMINE VALUES TO BE CONVERTED TO ANALOG
***** DYNAMICALLY
DYNBCU=-.01*MBCU
DZKU=.5*ZWUC
DXAI=.05*XAI
DZAI=.01*ZAI
DNAI=MA1C
DLVU=19.23*LVUC
DNVU=25.*NVUC
DNRU=.25*NRUC
DXTHU=.025*XTHUC
DZBIU=.001*ZBIUC
CALL DAC (16,DYNBCU,18,DZKU,21,DLVU,22,DNVU,23,DNRU,19,DXTHU,20,
1DZBIU)
CALL DAC (2,DXAI,3,DZAI,4,DMAI)
***** COMPUTE EULER ANGLES AND SCALE FOR COCKPIT INSTRUMENTS
*****

```



```

CALL ADK (4,Q2,5,P2,6,R2,10,DELARA)
SINPHI=SIN(PHI)
COSPHI=COS(PHI)
SINTHE=SIN(THETA)
C9STHE=COS(THETA)
P=.5*P2
G=.5*G2
R=.5*R2
41 THETAD=Q*C9SPHI-R*SINPHI
PSID=(G*SINPHI+R*COSPHI)/C9STHE
PHID=P+PSID*SINTHE
THETDS=-THETAD*1.862
PSIDS=-PSID*573
PHIDS=-PHID*1.91
***** COORDINATED TURN SYSTEM ****
* ***** TEST(3)*GE*0.0) G0 T0 304
* ***** IF (TEST(3)*GE*0.0) G0 T0 302
* ***** CALL SETLINES (1,-1)
* ***** DELARC=0.0
* ***** CALL ADK (9,DELA2)
* ***** CALL SETLINES (1,-1)
* ***** BETA=ATAN(V/U)
* ***** DELAIC=5*DELA2
* ***** DELARC=16.0*DELAIC+10.0*BETA-3.*PSID
* ***** CALL DAC (5,THETDS,6,PSIDS,7,PHIDS,11,DELARC)
* ***** CALL ADK (0,PHIS,1,PSIS,3,THETAS)
* ***** THETA=THETAS/1.862+THETIC
* ***** PSI=PSIS/.573
* ***** PHI=PHIS/1.91
* ***** ****

```



```

* COMPUTE SCALED EULER ANGLE FUNCTIONS FOR ANALOG
* ASINTH=-1.610*SINTHE
* AC00=0.322*C9SPHI*C9STHE
* ASIC0=1.610*SINPHI*C9STHE
* CALL DAC (8,ASINTH,9,AC00,C9,10,ASIC0)
* COMPUTE INERTIAL VELOCITIES
* CALL ADK (2,U4,7,V2,8,W2)
* U=250.*U4
* V=50.*V2
* W=50.*W2
* VPHTHX=U*C9STHE+V*SINPHI*SINTHE+W*C9SPHI*SINTHE
* VPHTHY=V*C9SPHI-W*SINPHI
* VPHTHZ=-U*SINTHE+V*SINPHI*C9STHE+W*C9STHE*C9SPHI
* C9PSI=C9S(PSI)
* SINPSI=SIN(PSI)
* VX=(VPHTHX*C9SPSI-VPHTHY*SINPSI)*(-1.)
* VY=VPHTHX*SINPSI-VPHTHY*C9SPSI
* VZ=VPHTHZ
* VZ1=VZ*.02
* CALL DAC (1,VZ1)
* AIRSPEED INDICATOR
* ASI=(59.00-4765*UK)*.01
* UK=U/1.687
* IF (UK.GT.60.) G9 T9 69
* ASI=(100.-(10./9.)*UK)*.01
* G9 T9 71
* 69 IF (UK.GT.90.) G9 T9 70
* ASI=(100.-(10./9.)*UK)*.01
* G9 T9 71
* ASI=-(100./55.)*UK-163.6)*.01
* 70 CALL DAC (12,ASI)
* 71

```



```

*****
* RADAR ALTIMETER
*****
CALL ADK(11,Z1)
ZE=5000.*Z1+500.
IF (ZE*GT*200.) G9 T8 400
IF (ZE*LT*100.) G9 T8 401
RADALT=-.40--.0001983*(ZE-100.)
G9 T8 415
IF (ZE*LT*70.) G9 T9 402
RADALT=-.345--.000183*(ZE-70.)
G9 T8 415
IF (ZE*LT*50.) G9 T8 403
RADALT=-.300--.000225*(ZE-50.)
G9 T8 415
IF (ZE*LT*40.) G9 T8 404
RADALT=-.2893--.000107*(ZE-40.)
G9 T8 415
IF (ZE*LT*20.) G9 T8 405
RADALT=-.2429--.000232*(ZE-20.)
G9 T8 415
RADALT=-.2129--.0015*ZE
G9 T8 415
RADALT=-.65
400  CALL DAC(17,RADALT)
*****
* COMPUTE INERTIAL POSITION
*****
CALL READCLK(DTNEW)
DT=DTNEW-DTOLD
SEC=DT*.0001
XE=XE+VX*SEC
YE=YE+VY*SEC
IF (SEC*LT*.0.) G9 T8 101
DTOLD=DTNEW

```



```

*****
* CREW DIRECTIONS IF WITHIN SIGHT OF TARGET
*****
* IF (XE.LT.3500.) GO T0 30
  GO T0 31
  IF (ZE.LT.400.) GO T0 32
  GO T0 31
  CALL CREW(IL,IR,SEC)
  **** AUTOMATIC SCAN PROGRAM CONTROL
  **** IF (TEST(6).LT.0) GO T0 900
  31  **** DIRECTION VELOCITY INDICATOR
  **** CALL DVI(VX,VY,VZ)
  GO T0 33
  **** AUTOMATIC SCAN PROGRAM
  **** CALL AUTSCN( SEC,MARK,VX,VY,VZ,UK,PSIS,PSID,DELARA )
  **** COMPUTE FLIGHT TIME
  **** FLTIN=DTNEW*.0001
  33  IF (FLTIN.LT.TIME) GO T0 35
      X(I)=XE
      Y(I)=YE
      Z(I)=ZE
      TIME=TIME+10.
      I=I+1
      IF (I.GT.120) I=120
      IF (TEST(2).LT.0.) GO T0 101
  35  IF (TEST(1).LT.0.) GO T0 99
  GO T0 98

```



```
101 CALL STOPCLOCK
      OUTPUT(6) XE,YE,ZE,VX,VY,THETA,PHI,PSI,FLTIME,SEC
      RETURN
      END
```



```

SUBROUTINE L90KUP (T,V,C)
DIMENSION T(7)
U=(ABS(V))/1.687
1F (U GT .30.) G8 T0 3
D=U/30.
D=U/30.

I=D+1
D=D-I+1
G8 T0 11
1F (U GT .70.) G8 T0 4
D=(U-30.)/20.
I=D+2
D=D-I+2
G8 T0 11
1F (U GT .112.) G8 T0 5
D=(U-70.)/21.
I=D+4
D=D-I+4
G8 T0 11
1F (U GT .136.) G8 T0 6
D=(U-112.)/24.
I=D+6
D=D-I+6
G8 T0 11
U=136.
G8 T0 5
C=T(I)+D*(T(I+1)-T(I))
RETURN
END

```

3

4

5

6 11

SUBROUTINE CREW(IL,IR,SEC)
 COMMON/STATE/VELB(3),ANGRAT(3),ANGLE(3),POSIT(3)

```

COMMON IDEV
COMMON X(120),Y(120),Z(120)
COMMON ITALK(9,14),IDVI(60),IND(20)
EQUIVALENCE (VELB(1),J),(VELB(2),V),(VELB(3),W),(ANGRAT(1),P),
1(ANGRAT(2),Q),(ANGRAT(3),R),(ANGLE(1),THETA),(ANGLE(2),PSI),
1(ANGLE(3),PHI),(POSIT(1),XE),(POSIT(2),YE),(POSIT(3),ZE)

IBACK=0
IF (XE*LT*0.) GE T0 22
***** START SLOWING DOWN-STEADY FORWARD ****
* IF (XE*GT*1500.) GE T0 6
***** READ GUT DISTANCE ****
***** EASY FORWARD ****
* IF (XE*GT*100.) GE T0 7
***** OVER TARGET ****
* IF (XE*LT*40.) GE T0 21
  T0LD=0.0
  5  J=3
    GS T0 4
  7  J=2
    CALL TEXT0(IDEV,IX,1,34,1,3,IER)
    GS T0 24
*****
```



```

*      EVERSHOT TARGET- EASY BACK
*      **** * **** * **** * **** * **** * **** * **** * **** * **** * ****
*      22      IF (XE•LT•300•) G8 T9 18
*      ENCODE(4,300,IX) XE
*      CALL TEXT0(IDEV,IX,1,34, 1,3,3,IER)
*      IF (XE•GT•40•) G8 T9 21
*      T0LD=0.0
*      J=4
*      IBACK=1
*      G8 T9 23
*      J=10
*      H9VT1Y=SEC+T0LD
*      T0LD=H9VT1Y
*      IF (H9VT1Y•GT•30•) J=11
*      IF (H9VT1Y•GT•45•) J=12
*      CALL TEXT0(IDEV,ITALK(1,J),9,34,17,3, 3,IER)
*      23      IF (YE•LT•0•) G8 T9 8
*      24      IF (YE•LT•0•) G8 T9 8
*      *      T09 FAR TE RIGHT- EASY LEFT
*      *      **** * **** * **** * **** * **** * **** * **** * **** * ****
*      *      IF (YE•GT•100•) G8 T9 50
*      *      **** * **** * **** * **** * **** * **** * **** * **** * ****
*      *      STOP EASY LEFT
*      *      **** * **** * **** * **** * **** * **** * **** * **** * ****
*      *      IF (YE•GT•40•) T0LD=0.0;G8 T9 51
*      *      **** * **** * **** * **** * **** * **** * **** * **** * ****
*      *      EVER TARGET
*      *      **** * **** * **** * **** * **** * **** * **** * **** * ****
*      *      J=14
*      *      G8 T9 52
*      51      J=9
*      IF (IL•EG•0) J=6
*      IF (YE•LT•50•) J=9
*      G8 T9 59
*      J=6

```



```
18      J=14
      CALL TEXT9( IDEV, ITALK(1,J), 9, 34, 17, 3,
      CALL TEXT9( IDEV, ITALK(1,J), 9, 37, 20, 3,
      CALL TEXT8( IDEV, ITALK(1,J), 9, 40, 20, 3,
      IX=-1
      CALL TEXT8( IDEV, IX, 1, 34, 1, 3, 3, IER)
      69  TO 17
      J=1
      CALL TEXT9( IDEV, ITALK(1,J), 9, 34, 17, 3,
      17      IF (IER.NE.0) OUTPUT (6) IER
      RETURN
      END
```



```

SUBROUTINE DV1(VX,VY,VZ)
COMMON IDEV
COMMON X(120),Y(120),Z(120)
COMMON ITALK(9,14),IDVI(60),IND(20)
VZ=-VZ*60.
IND(1)=IHEAD(0,10)
**** RATE OF DESCENT INDICATOR ****
IF (VZ.GT.1200.) VZ=1200.
IF (VZ.LT.-1200.) VZ=-1200.
YA=.000417*VZ+.2
IND(2)=IPACK(.-9,YA,0)
IND(3)=IPACK(.-8,YA,1)
**** HORIZONTAL BAR- FORWARD VELOCITY ****
IF (VX.GT.59.01) VX=59.01
IF (VX.LT.-59.01) VX=-59.01
YU=.01186*VX+.2
IND(4)=IPACK(.-5,YU,0)
IND(5)=IPACK(.9,YU,1)
**** VERTICAL BAR- SIDEWARD VELOCITY ****
VY=-VY
IF (VY.GT.59.01) VY=59.01
IF (VY.LT.-59.01) VY=-59.01
VX=.01186*VY+.2
IND(6)=IPACK(XV,.9,0)
IND(7)=IPACK(XV,-.5,1)
IND(8)=0
CALL GRAPH9(IDEV,IND,8,2,IER)
RETURN

```



```

IHDG(3)=IPACK( -7, 5, ID)
IHDG(4)=IPACK( -6, 6, ID)
IHDG(5)=IPACK( -7, 5, 0)
IHDG(6)=IPACK( -6, 4, ID)
66 TE 453
*****
*   RIGHT TURN
*****
451   IHDG(2)=IPACK( 4, 5, 0)
      IHDG(3)=IPACK( 7, 5, ID)
      IHDG(4)=IPACK( 6, 5, ID)
      IHDG(5)=IPACK( 7, 5, 0)
      IHDG(6)=IPACK( 6, 4, ID)
      IHDG(7)=0
      CALL GRAPH6(IODEV, IHDG, 7, 1, IER)
      IF (SCNTIM.GT.T8TSC1) MARK=0; SCNTIM=0.
      IF (MARK.EQ.1) GO T9 400
      TOLD=0.0
      MARK=1
      SCNTIM=SEC+TOLD
      TOLD=SCNTIM
*****
470   IF (SCNTIM.GT.T8TSC1) MARK=0; SCNTIM=0.
      IF (MARK.EQ.1) GO T9 400
      TOLD=0.0
      MARK=1
      SCNTIM=SEC+TOLD
      TOLD=SCNTIM
*****
      ATTITUDE PRESENTATION
*****
      SCNT1=2.0
      IF (SCNTIM.GT.SCNT1) GO T9 401
      IGYR9(1)=IHEAD(0,10)
*****
      MINIATURE AIRPLANE
*****
      IGYR9(2)=IPACK( -5, 0, 0)
      IGYR9(3)=IPACK( -2, 0, 1)
      IGYR9(4)=IPACK( -1, -1, 1)
      IGYR9(5)=IPACK( 0, 0, 1)
      IGYR9(6)=IPACK( 1, -1, 1)

```



```

IDRIFT(18+M)=IPACK(XL,.1,1)
IDRIFT(19+M)=IPACK(XL+.2,.3,0)
M=Y+.2
XL=XL+.2
CONTINUE
*****
* HORIZONTAL BAR - FORWARD VELOCITY
*****
* IF (VX>59.01) VX=59.01
* IF (VX<59.01) VX=-59.01
YU=.01186*VX+.2
IDRIFT(32)=IPACK(-.5,YU,0)
IDRIFT(33)=IPACK(.5,YU,1)
*****
* VERTICAL BAR - SIDEWARD VELOCITY
*****
* VY=-VY
IF (VY>59.01) VY=59.01
IF (VY<59.01) VY=-59.01
XV=.01186*VY+.2
IDRIFT(34)=IPACK(XV,.9,0)
IDRIFT(35)=IPACK(XV,-.5,1)
*****
* VERTICAL SPEED INDICES
*****
IDRIFT(36)=IPACK(-.9,.6,0)
IDRIFT(37)=IPACK(-.7,.6,1)
IDRIFT(38)=IPACK(-1.0,.4,0)
IDRIFT(39)=IPACK(-.7,.4,1)
IDRIFT(40)=IPACK(-.9,.2,0)
IDRIFT(41)=IPACK(-.7,.2,1)
IDRIFT(42)=IPACK(-1.0,.0,0)
IDRIFT(43)=IPACK(-.7,.0,1)
IDRIFT(44)=IPACK(-.9,-.2,0)
IDRIFT(45)=IPACK(-.7,-.2,1)

```



```

IDRIFT(46)=IPACK(-1,0,-4,0)
IDRIFT(47)=IPACK(-7,-4,1)
IDRIFT(48)=IPACK(-9,-6,0)
IDRIFT(49)=IPACK(-7,-6,1)
* VERTICAL SPEED INDICATOR
* VZMIN=VZ*60.
RATE=-0.0004*VZMIN
IDRIFT(50)=IPACK(-7,RATE,0)
IDRIFT(51)=IPACK(-6,RATE,1)
IDRIFT(52)=0
IDRIFT(53)=0
CALL GRAPH9(IDEV, IDRIFT, 53, 2, IER)
GE TB 454.
* AIRSPEED PRESENTATION
* SCAS1=4.0
IF (SCNTIM.GT.SCAS1) GE TB 403
IAIR(1)=IHEAD(0,10)
* CHANGE IN VELOCITY INDICES
402  IAIR(2)=IPACK(-5,0,0)
IAIR(3)=IPACK(-6,0,1)
IAIR(4)=IPACK(-5,0,0)
IAIR(5)=IPACK(-7,0,1)
IAIR(6)=IPACK(-5,0,0)
IAIR(7)=IPACK(-6,0,1)
IAIR(8)=IPACK(-5,0,0)
IAIR(9)=IPACK(-9,0,1)
IAIR(10)=IPACK(-5,0,0)
IAIR(11)=IPACK(-6,0,1)
IAIR(12)=IPACK(-5,0,0)

```



```

IALT(6) = IPACK( -0.9, 0.2, 0)
IALT(7) = IPACK( -0.7, 0.2, 1)
IALT(8) = IPACK( -1.0, 0.0, 0)
IALT(9) = IPACK( -0.7, 0.0, 1)
IALT(10) = IPACK( -0.9, -0.2, 0)
IALT(11) = IPACK( -0.7, -0.2, 1)
IALT(12) = IPACK( -1.0, -0.4, 0)
IALT(13) = IPACK( -0.7, -0.4, 1)
IALT(14) = IPACK( -0.9, -0.6, 0)
IALT(15) = IPACK( -0.7, -0.6, 1)
*****
***** RATE OF CHANGE INDICATOR
*****
* VZMIN=VZ*60.
RATE=-.0004*VZMIN
IALT(16) = IPACK( -0.7, RATE, 0)
IALT(17) = IPACK( -0.6, RATE, 1)
IALT(18)=0
*****
***** ALTITUDE INDICATION
*****
***** ENCODE(4,301,IZE(1)) ZE
IZE(2)=-1
CALL TEXT9(IDEV,IZE,2,20,50,3,3,IER)
CALL GRAPH9(IDEV,IALT,18,2,IER)
GO TO 454
CALL TEXT9(IDEV,NULL,1,20,50,3,3,IER)
RETURN
END

```


0.0	• 2328	-1 • 5014	-3 • 8143	-6 • 8470	-10 • 6184	-15 • 5095
0.0	-9 • 2718	-5 • 8539	• 6023	6 • 5540	18 • 7617	34 • 3457
0.0	• 1417	• 1940	• 2244	• 2610	• 2456	• 1835
- • 4045	- • 5092	- • 5843	- • 6368	- • 6682	- • 6875	- • 6928
-12 • 1694	-12 • 2229	-12 • 3438	-12 • 5480	-12 • 8240	-13 • 0365	-13 • 1535
- • 0215	• 0261	- • 0298	- • 0352	- • 0409	- • 0464	- • 0519
- • 5871	- • 7410	- • 8881	-1 • 0799	-1 • 2692	-1 • 4471	-1 • 6220
• 0172	• 0202	• 0227	• 0272	• 0312	• 0352	• 0399
25 • 06	22 • 88	21 • 96	19 • 942	17 • 55	17 • 617	20 • 454
4 • 5674	35 • 3516	64 • 7892	97 • 4090	131 • 0581	164 • 4026	197 • 3886
STEADY FORWARD						
EASY FORWARD						
STEP EASY FORWARD, STEADY HOVER						
EASY BACK						
STEP EASY BACK, STEADY HOVER						
EASY LEFT						
STEP EASY LEFT, STEADY HOVER						
EASY RIGHT						
STEP EASY RIGHT, STEADY HOVER						
STEADY HOVER						
MAN ON HOIST						
MAN IN AIRCRAFT						
COME UP YOU ARE LOW						

APPENDIX B

The Analog Program

This appendix contains schematics illustrating the analog program. The six equations of motion, instrument inputs, and program control are incorporated in the schematics.

TABLE BI
USE OF TRUNKLINES

T000	200 $\Delta\theta_c$
T001	200 ΔA_{lc}
T002	100 ΔB_{lc}
T003	+30 VDC
T004	-30 VDC
T005	AIRSPEED
T006	BALL
T007	TURN NEEDLE
T010	HEADING (NOT USED)
T011	ALTIMETER
T014	RADAR ALTIMETER
T015	PITCH ATTITUDE
T016	ROLL ATTITUDE
T017	VERTICAL SPEED
T020	500 $\Delta\theta_R$
T023	"FLY"
T024	"STOP RUN"
T025	"QUIT"
T026	"RERUN"
T030	COORDINATED TURN
T041	AUTOMATIC SCAN

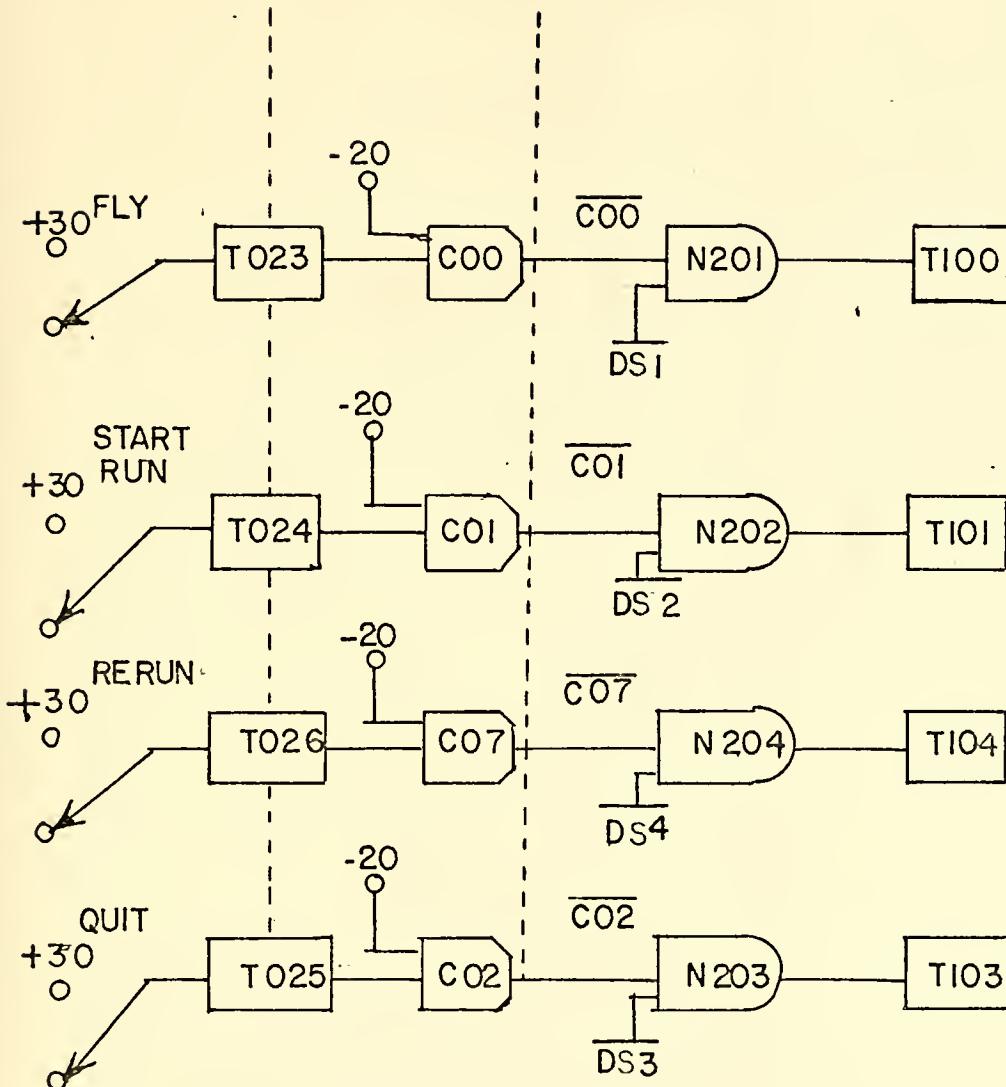
TABLE BII
ANALOG POTENTIOMETER SETTINGS

<u>POT NUMBER</u>	<u>SETTING</u>	<u>POT NUMBER</u>	<u>SETTING</u>
000	.0890	030	.4000
001	.4724	031	.1816
002	.1320	032	.9127
003	.2006	033	.1021
004	.0869	034	.6062
005	.1962	035	.2598
006	.0800	036	.4000
010	.0100	037	.2500
011	.1224	040	.1093
012	.2500	041	.0018
013	.1250	042	.4692
014	.0100	043	.1186
015	.0838	044	.4000
016	.0250	045	.1250
017	.7075	046	.6250
020	.7853	047	.2500
021	.0389	050	.3200
022	.1066	051	.1041
023	.0241	052	.2000
024	.2000	053	.1052
025	.5000	054	.1052
026	.2850	055	.6282
027	.0845	056	.5000

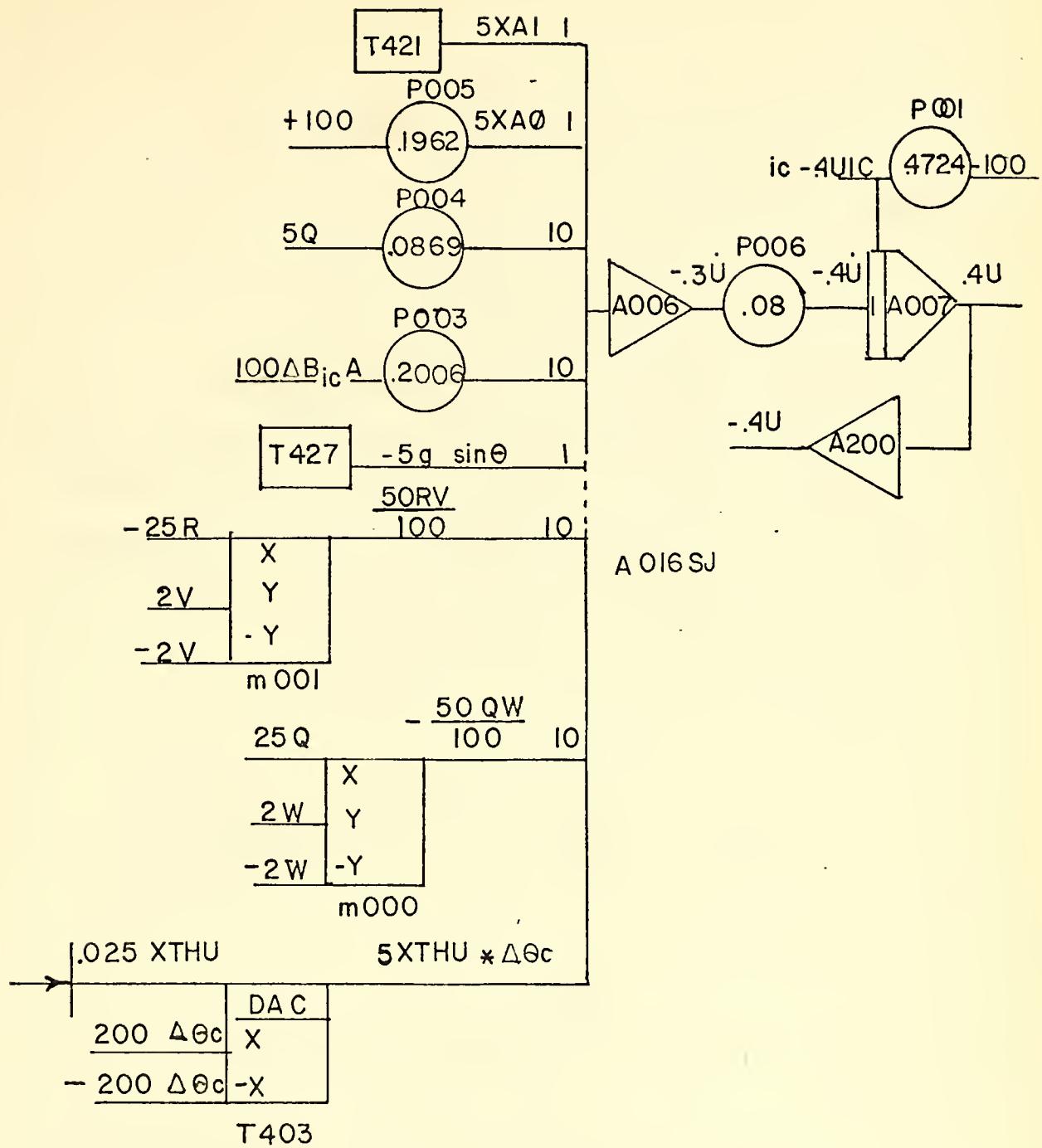
COCKPIT

ANALOG

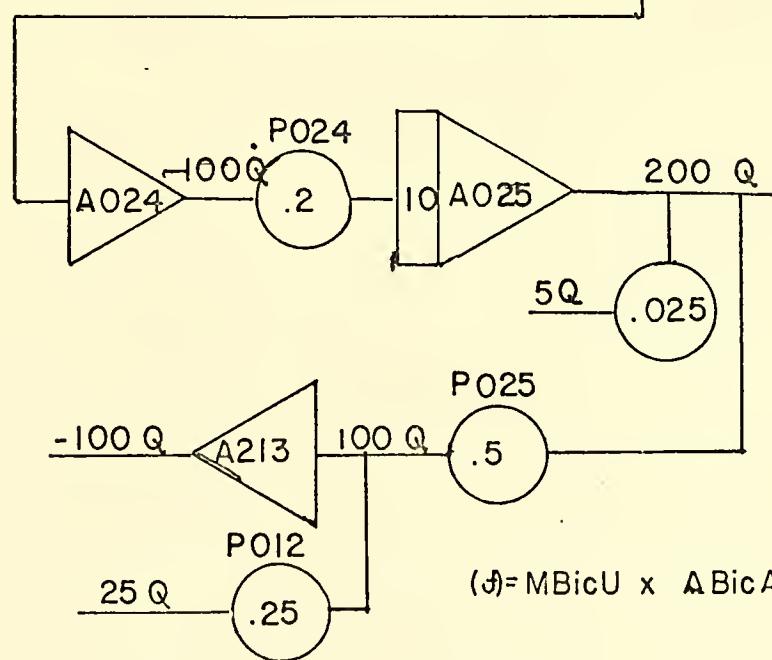
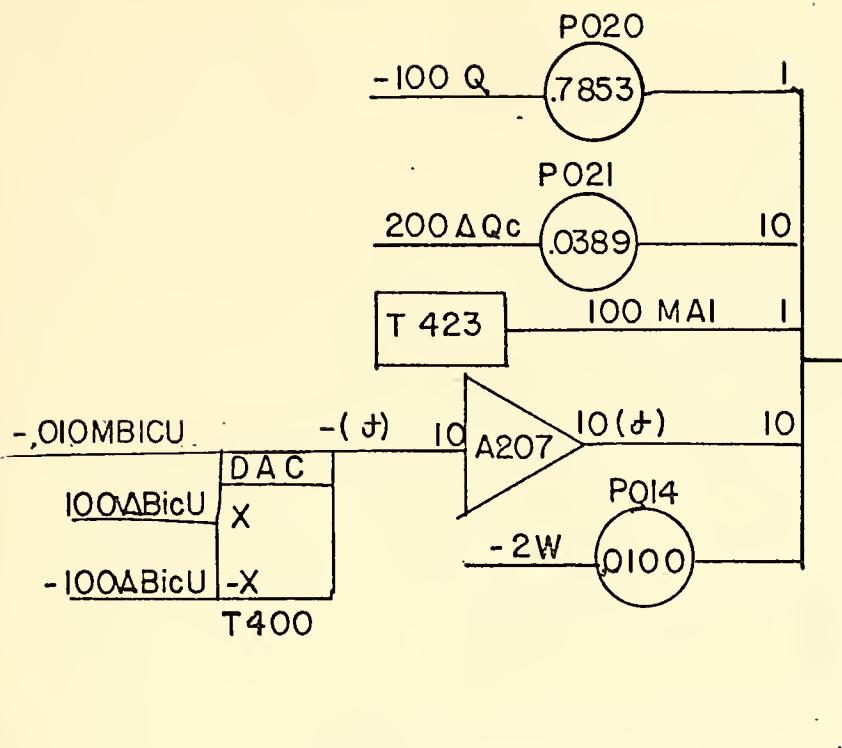
LOGIC



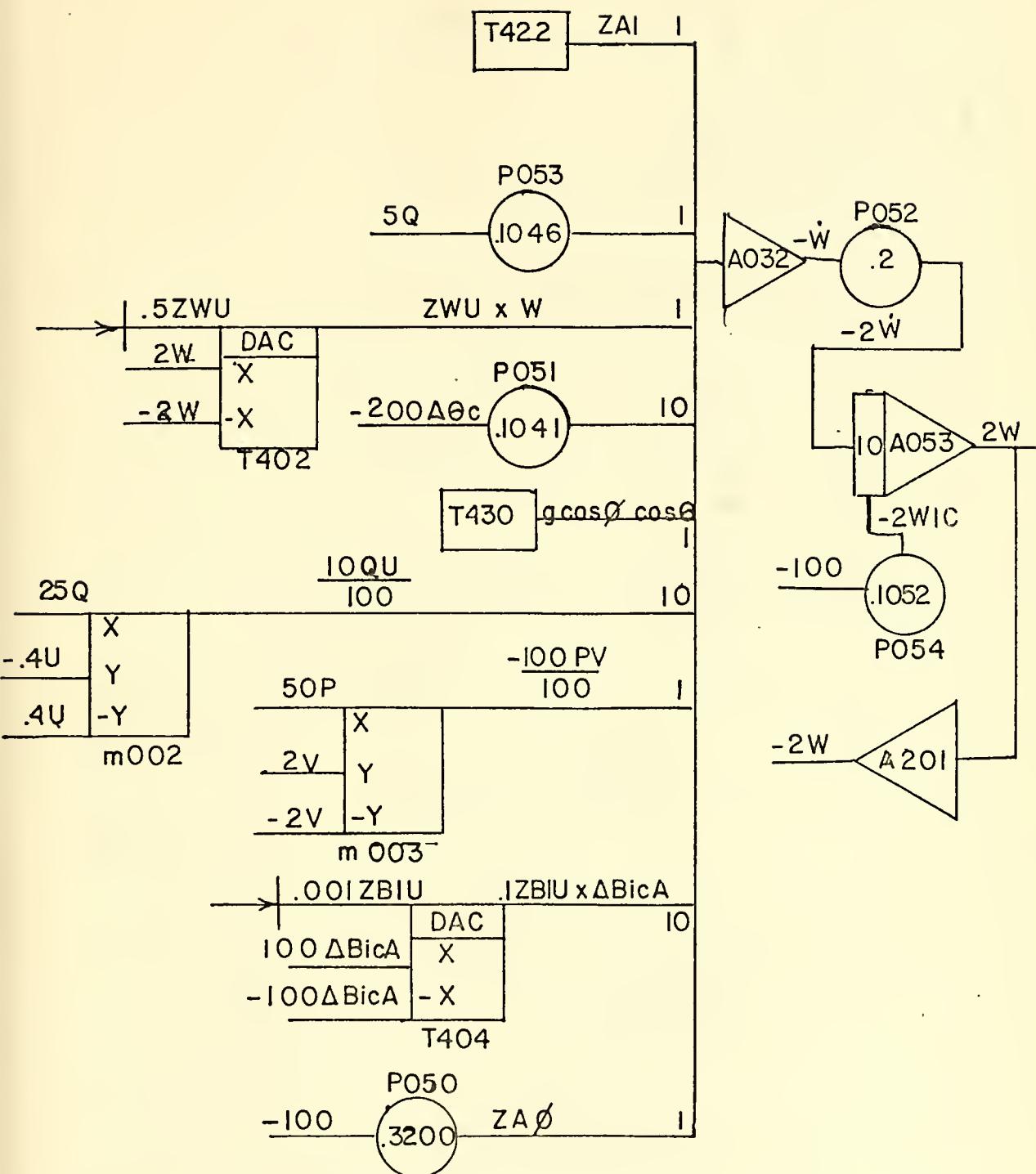
SIMULATOR CONTROL



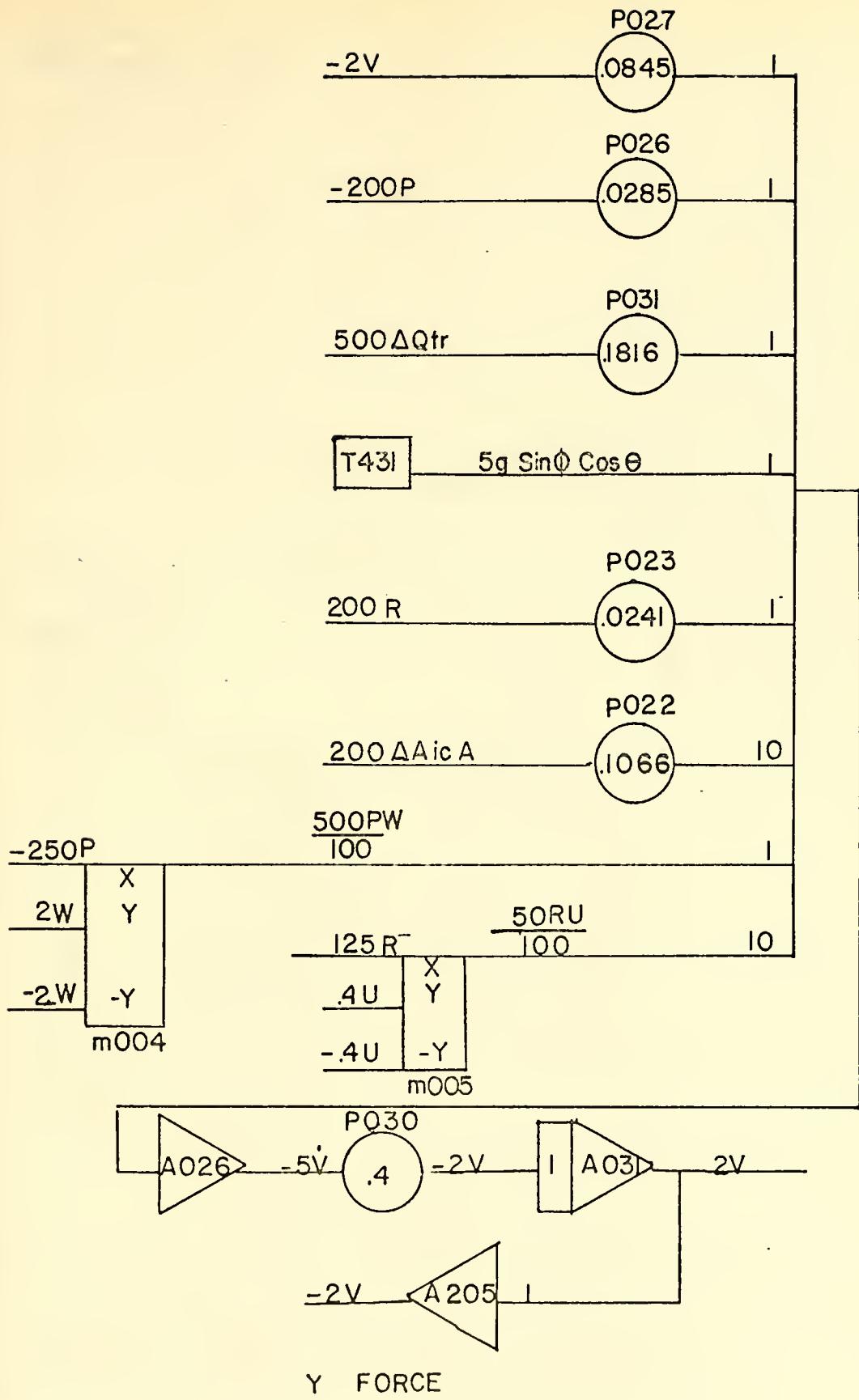
X FORCE

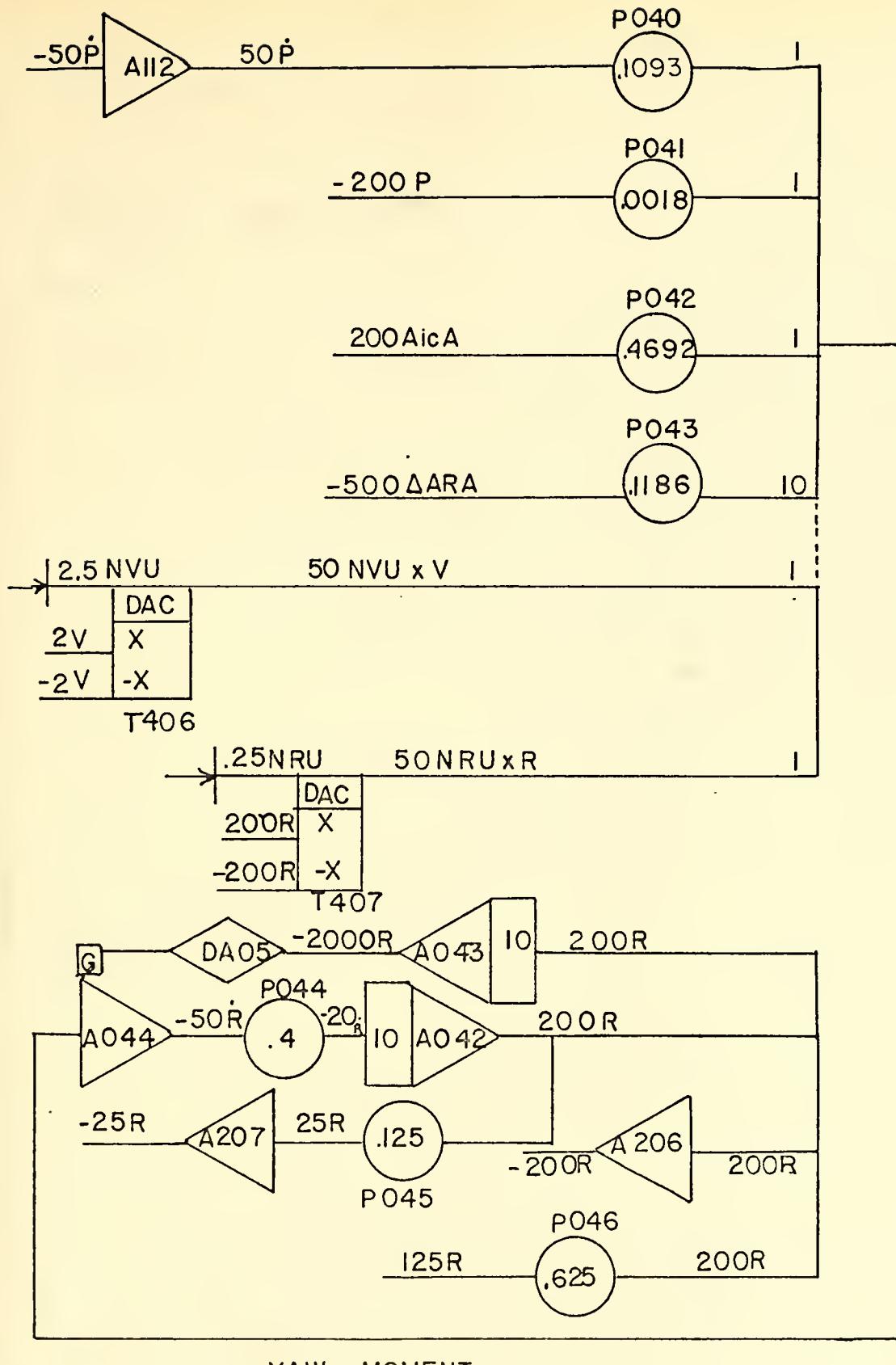


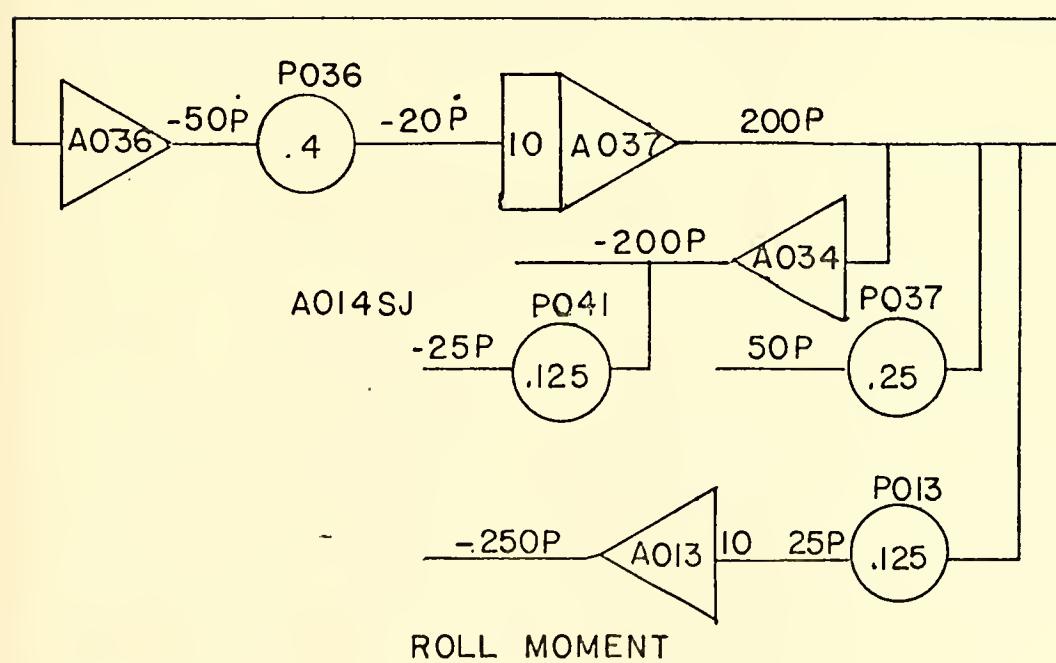
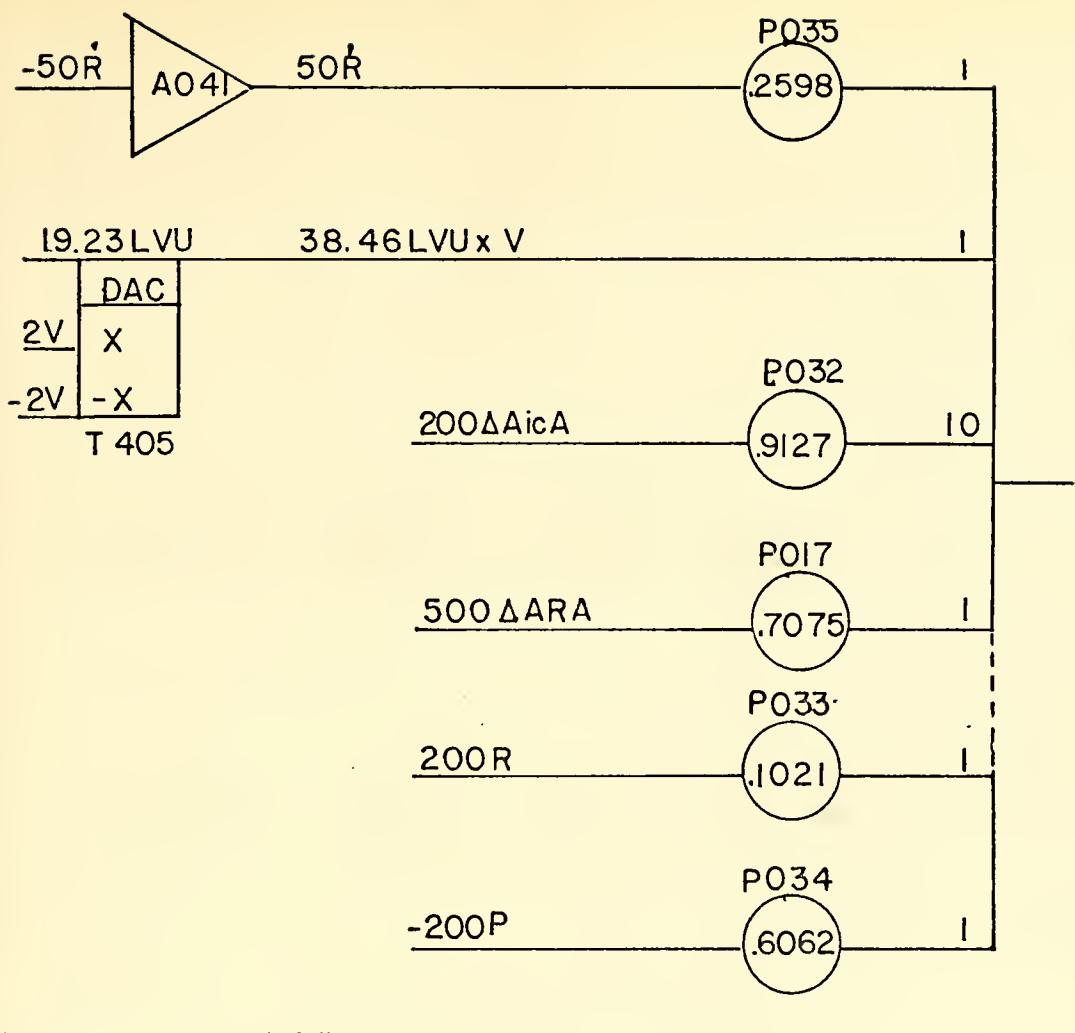
PITCH MOMENT

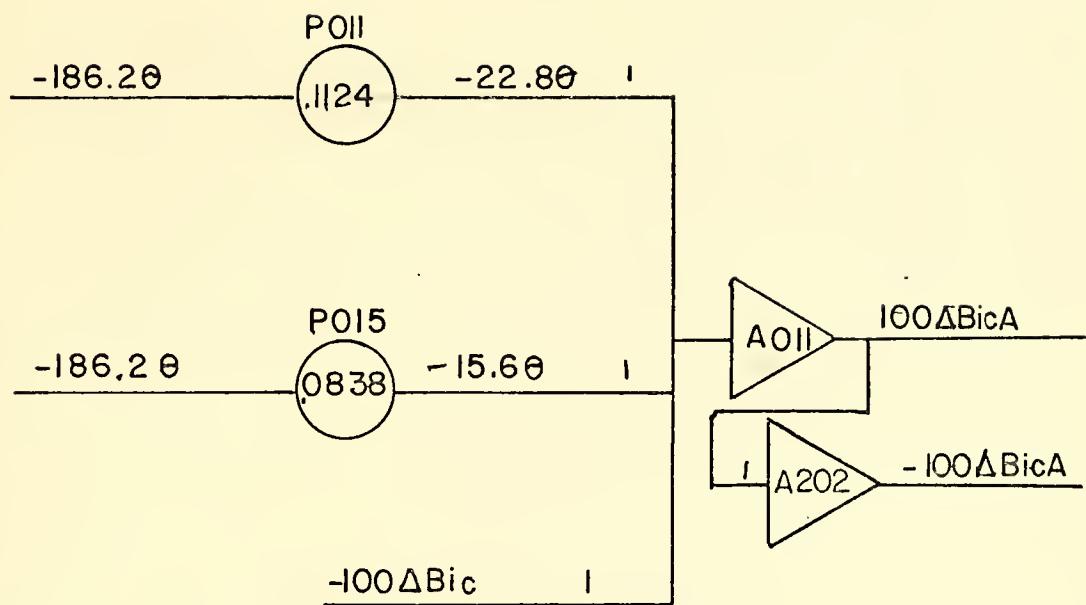


Z FORCE

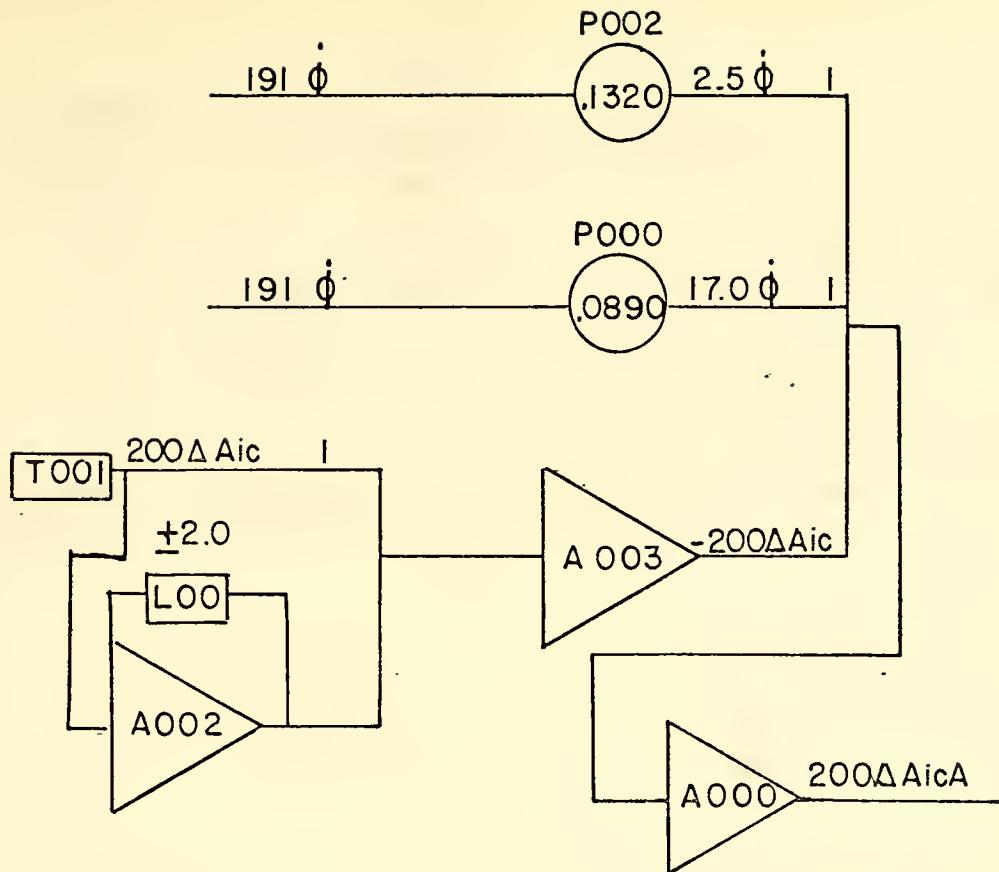




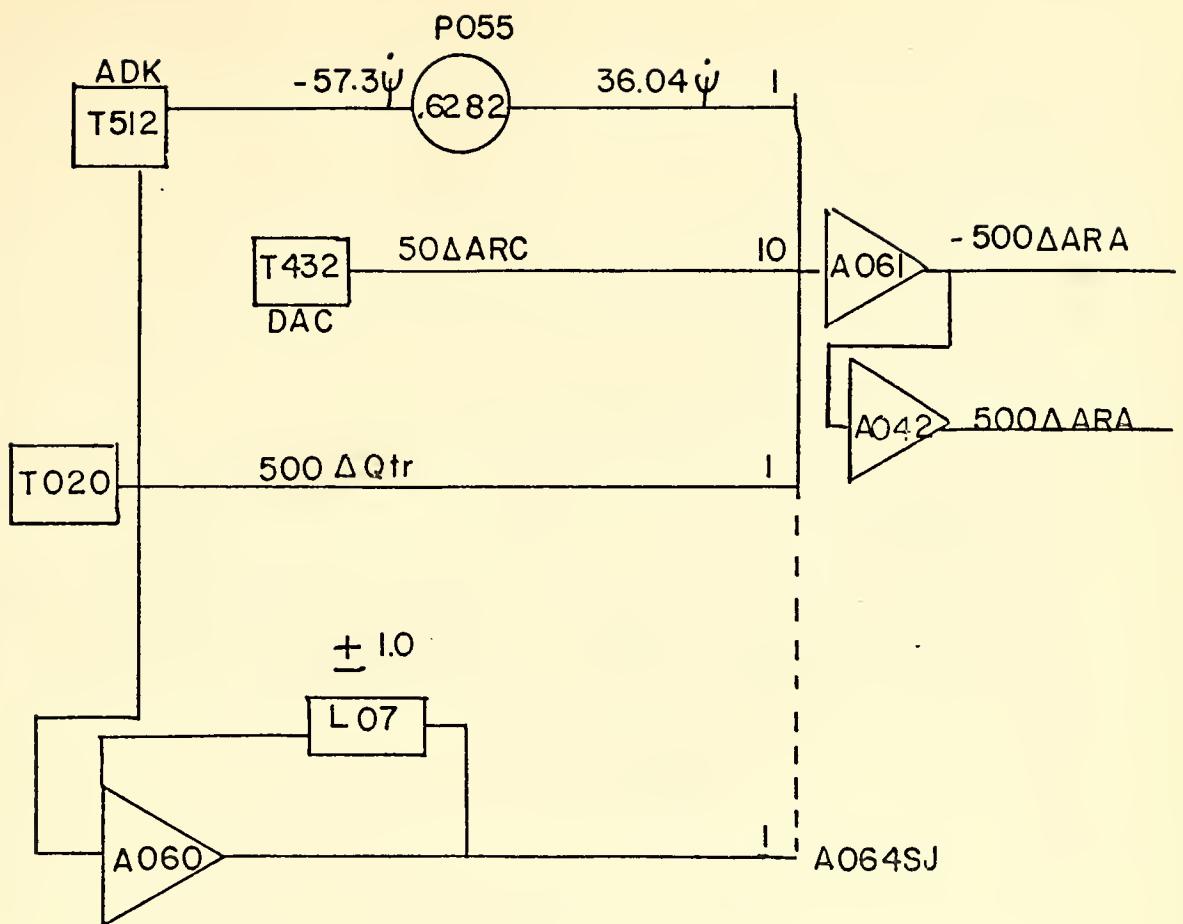




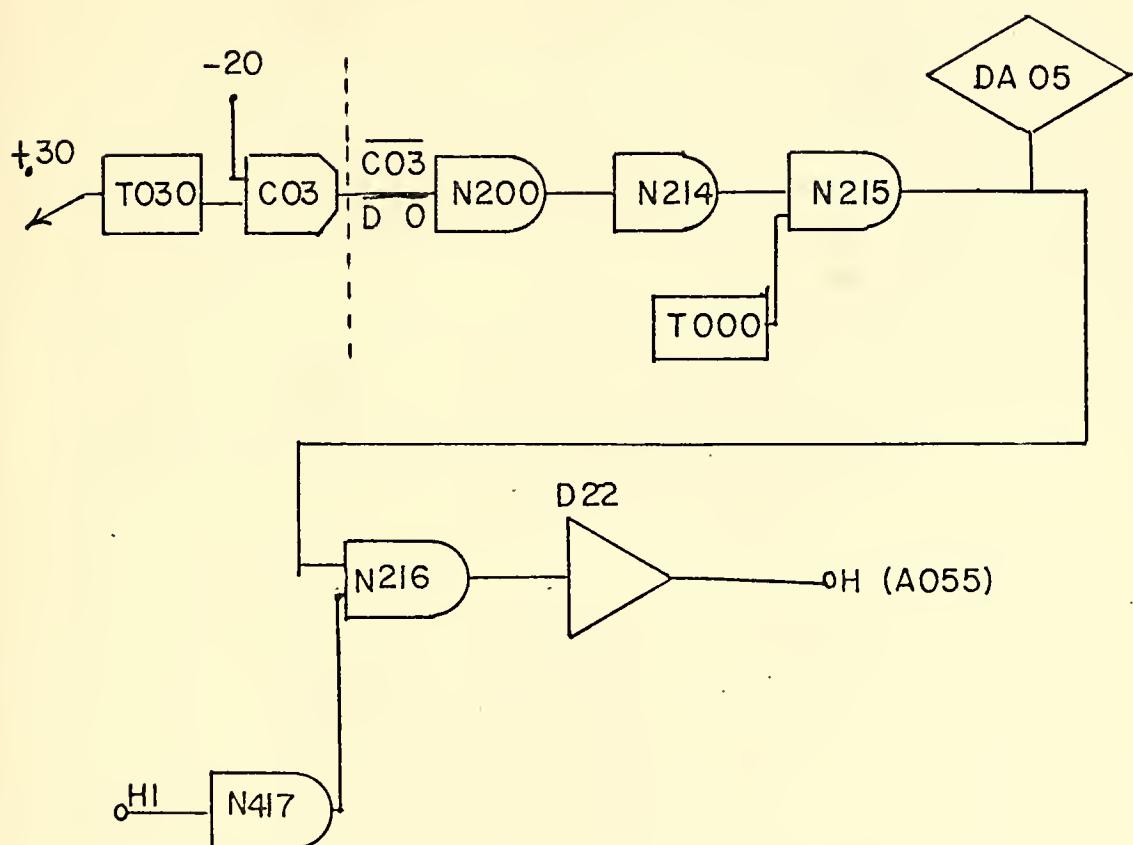
PITCH AUGMENTATION



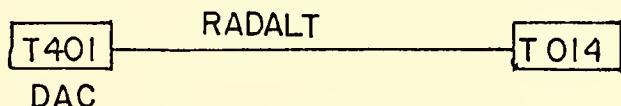
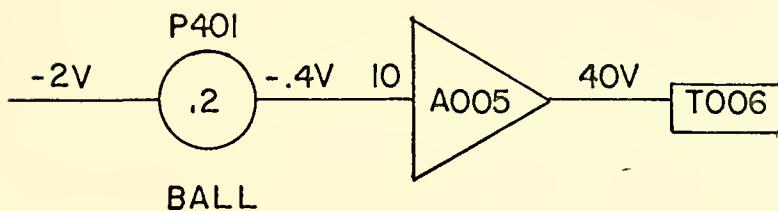
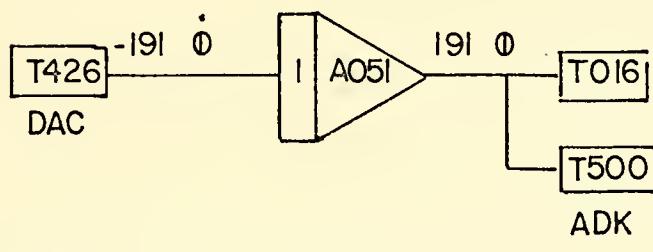
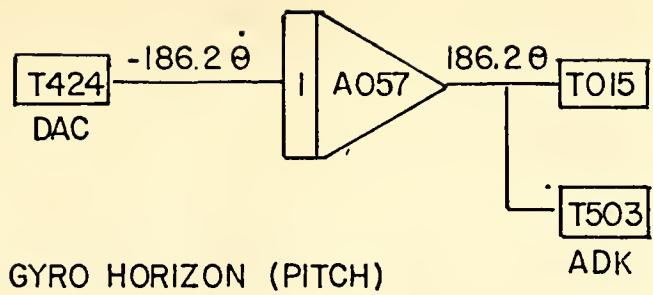
ROLL AUGMENTATION



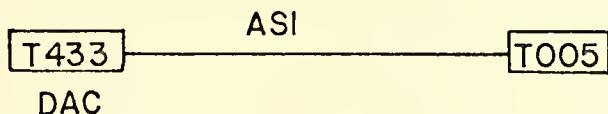
YAW AUGMENTATION



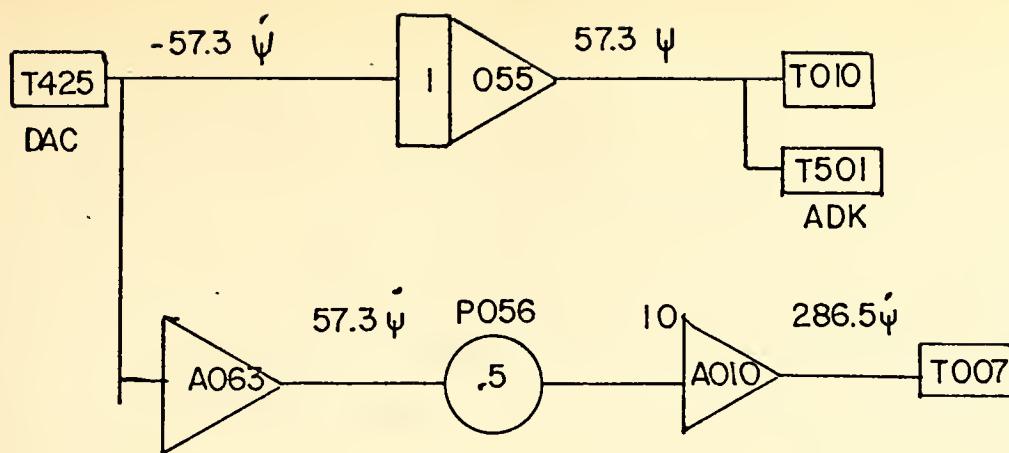
COORDINATED TURN



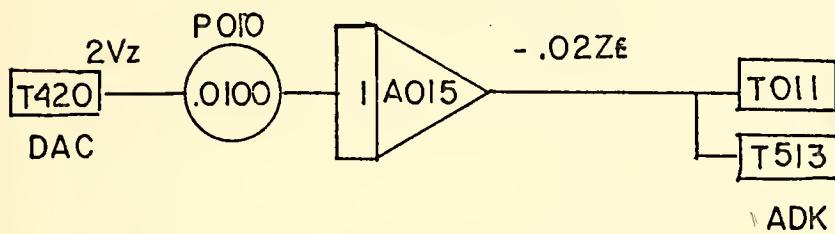
RADAR ALTIMETER



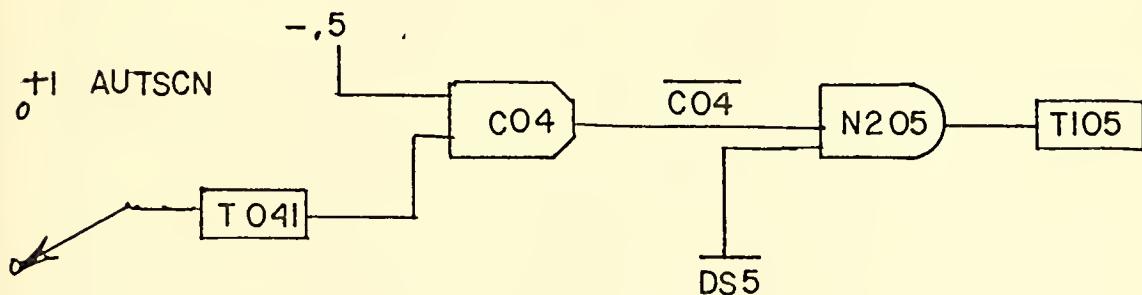
AIRSPEED INDICATOR



HEADING AND RATE OF TURN



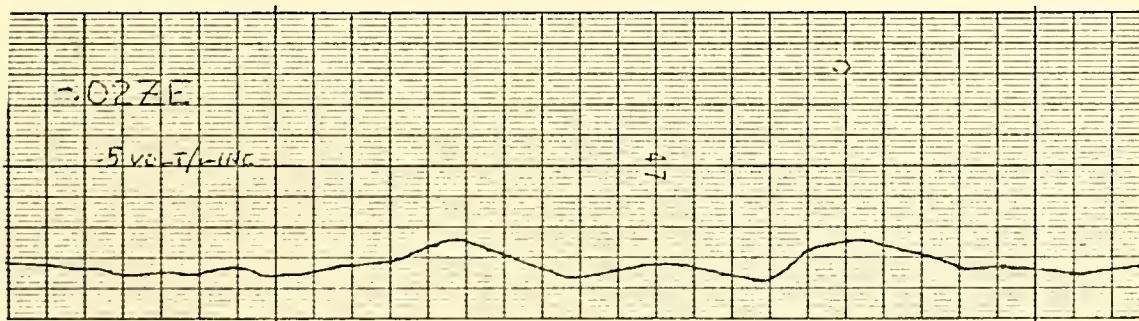
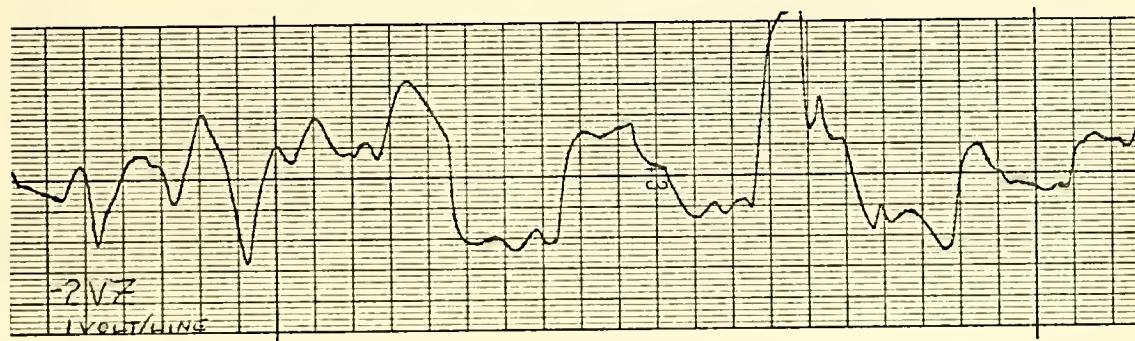
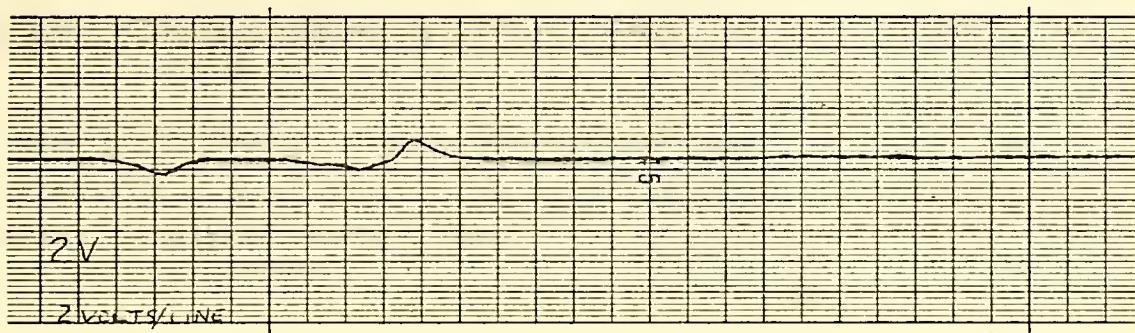
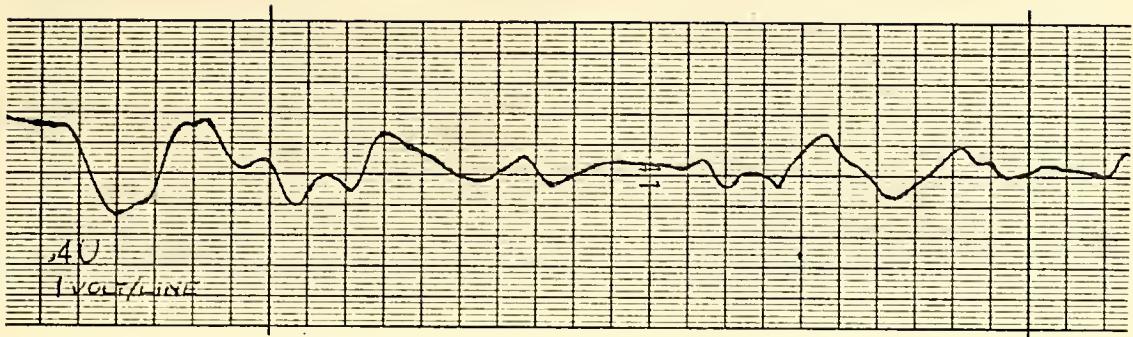
ALTIMETER AND VERTICAL SPEED INDICATOR



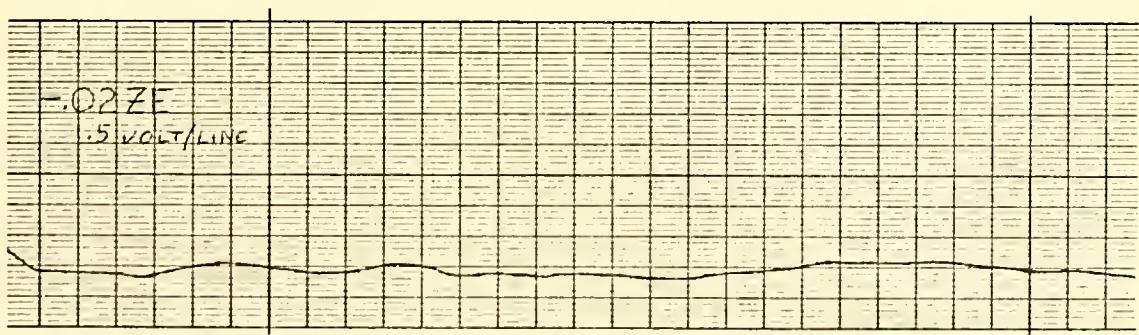
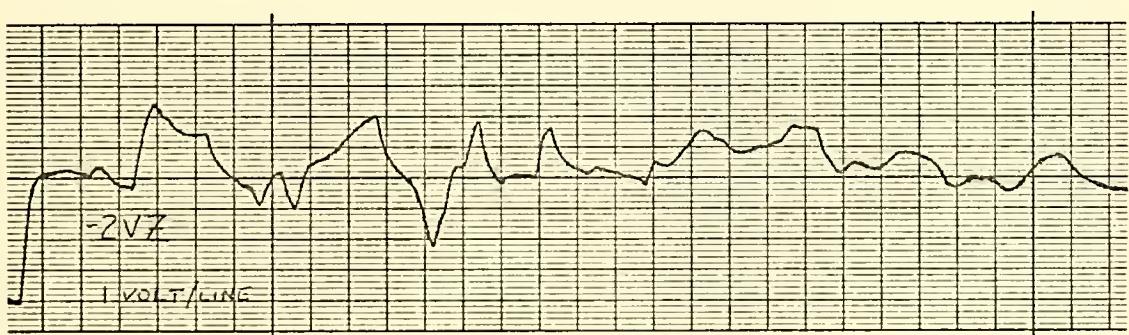
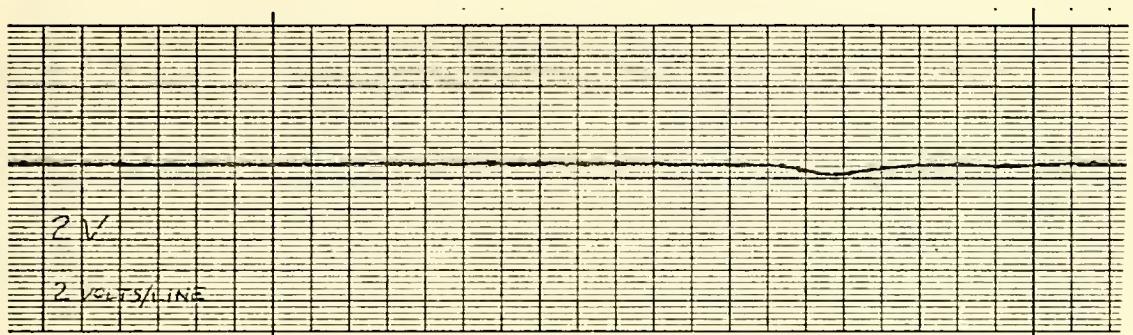
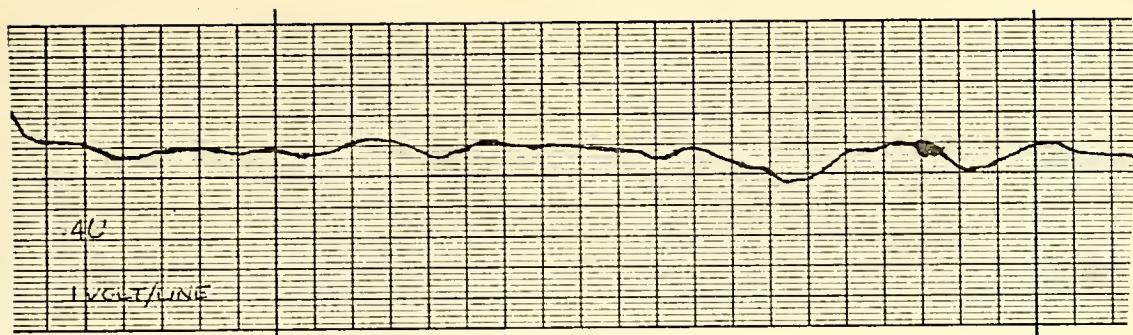
AUTOMATIC SCAN CONTROL

APPENDIX C
Evaluation Flight Traces

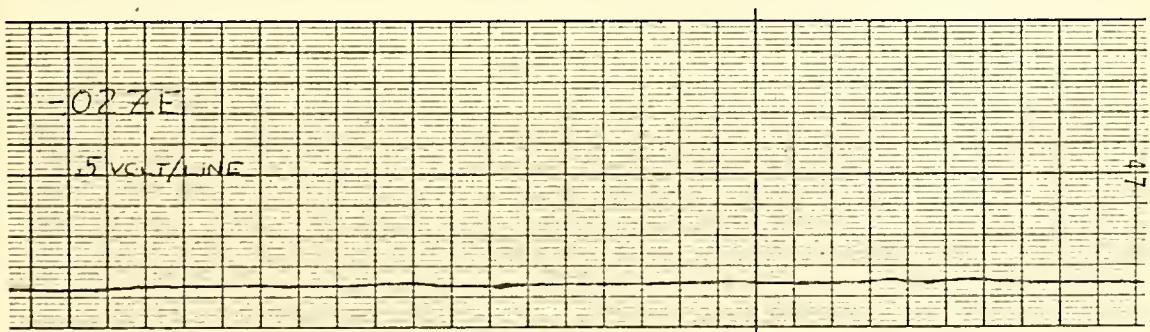
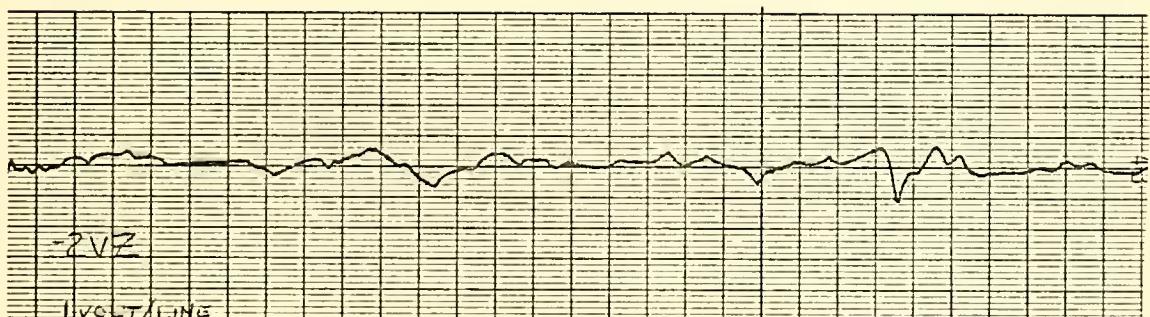
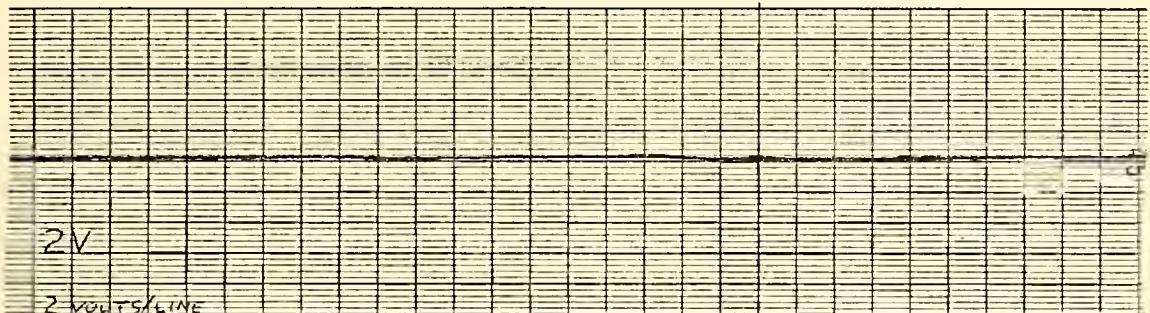
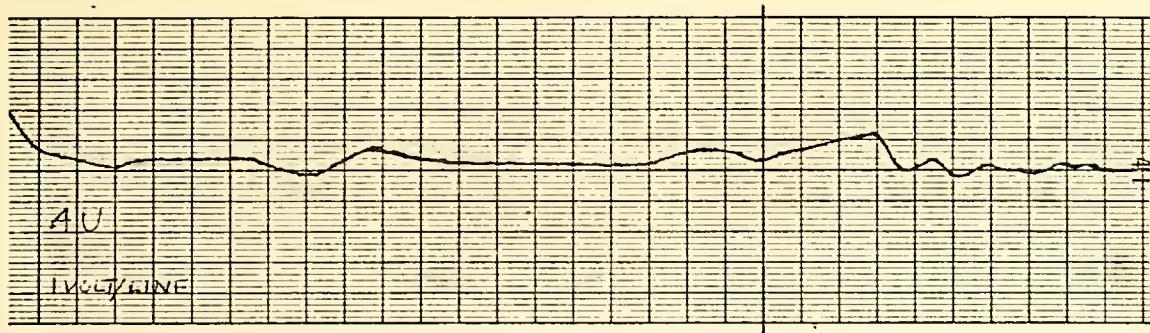
This appendix contains stripchart recordings of u, v, V_z , and Z_E for each evaluation pilot and both scan systems. The recordings were made during the transition and hover portions of the flights. The chart speed was .5 mm/sec.



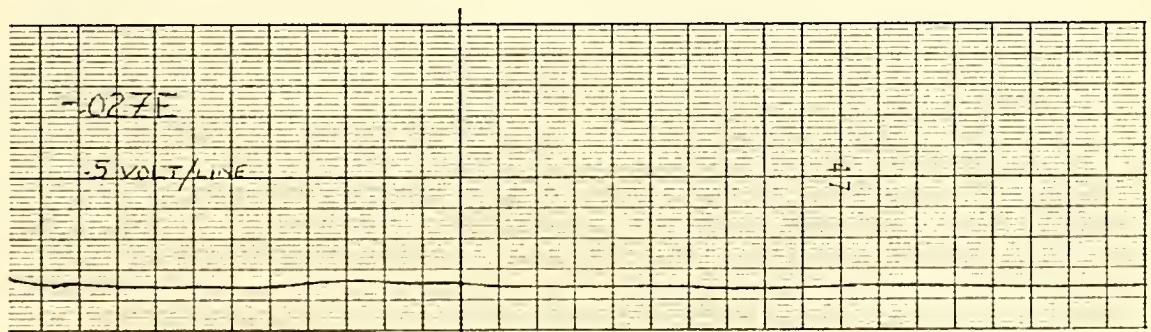
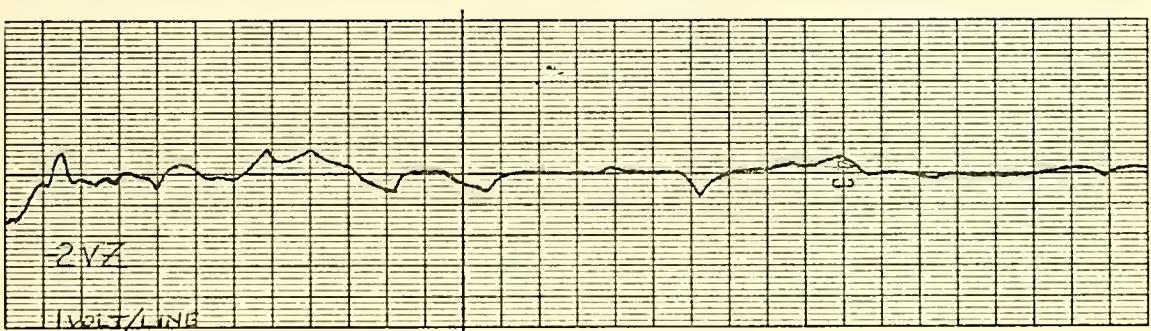
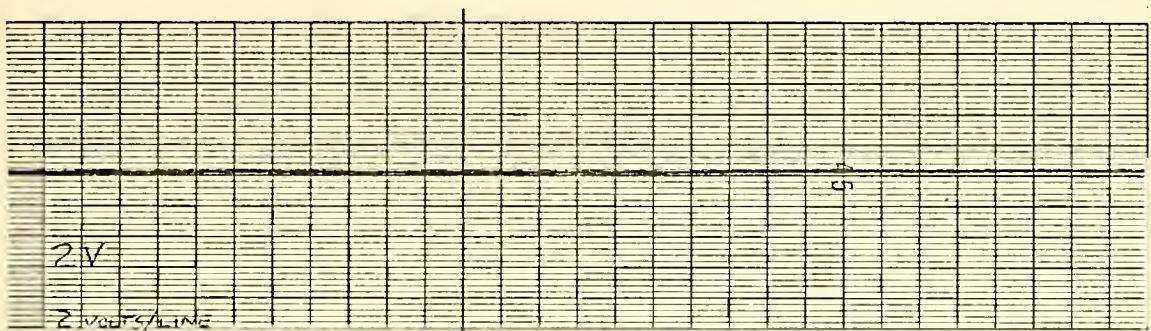
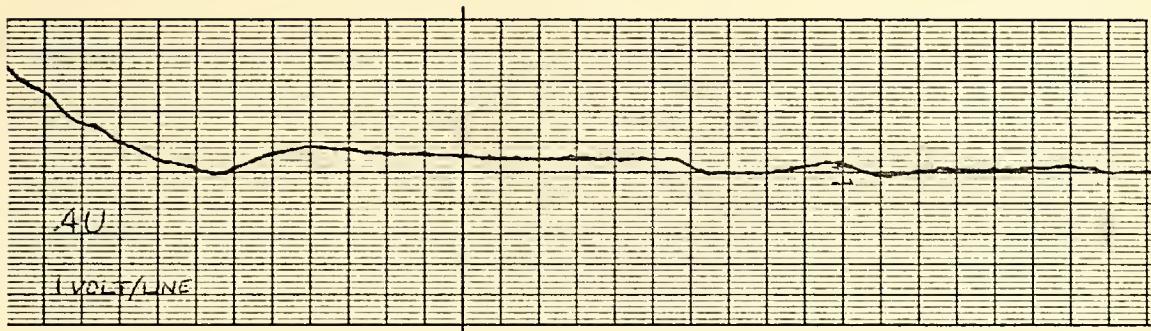
PILOT A, NORMAL



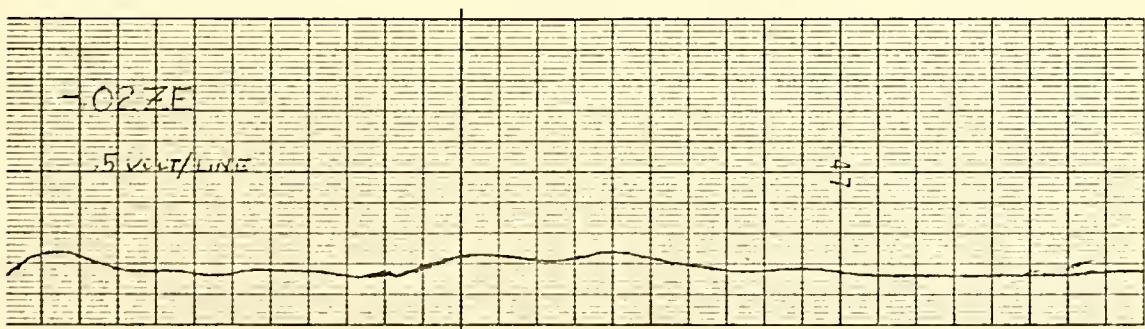
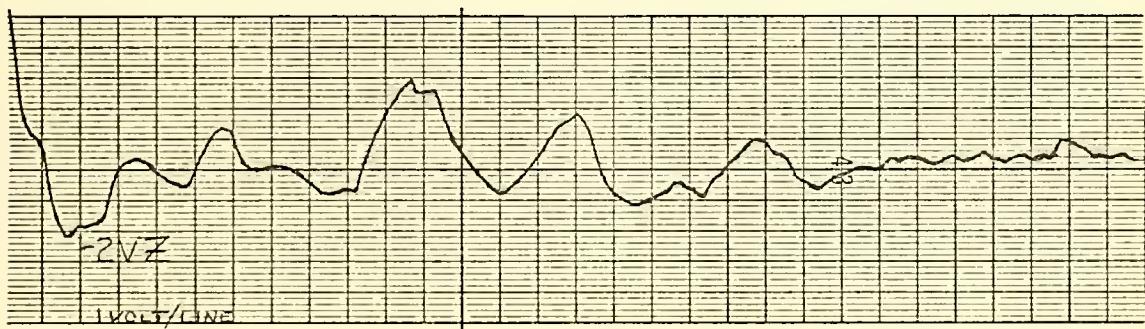
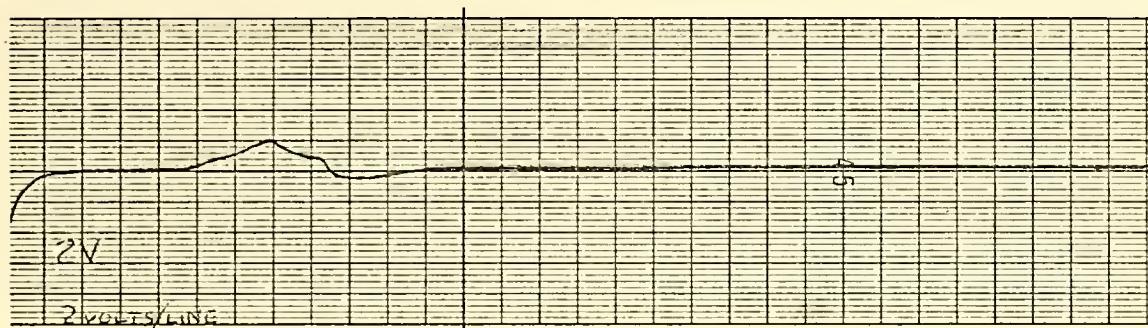
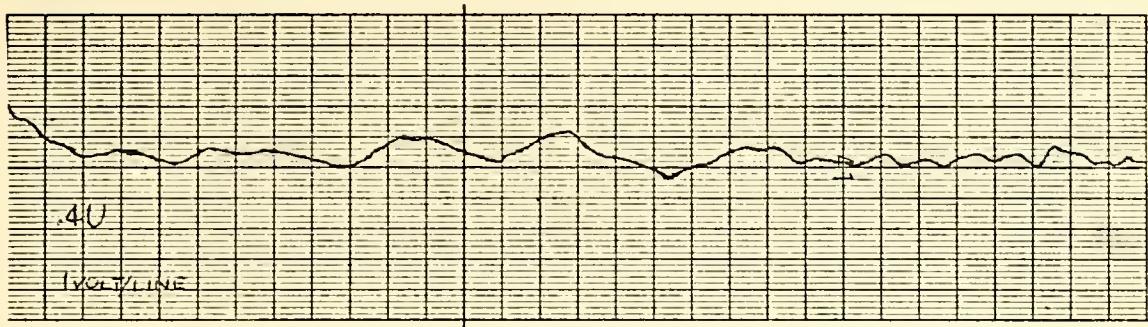
PILOT A, AUTOMATIC



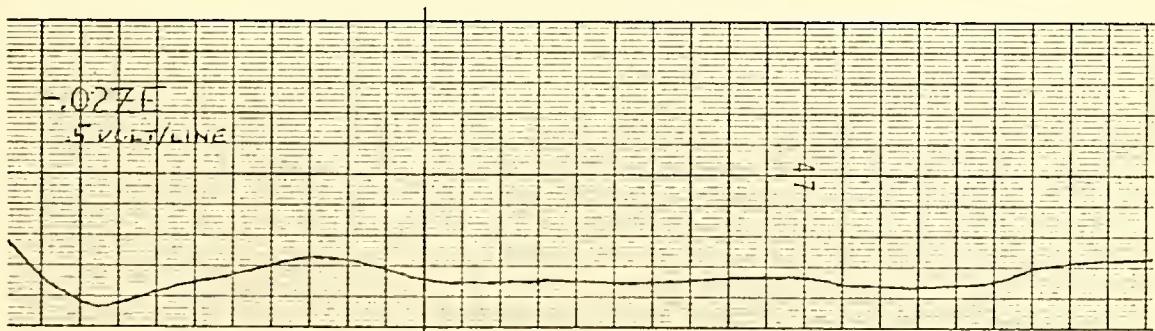
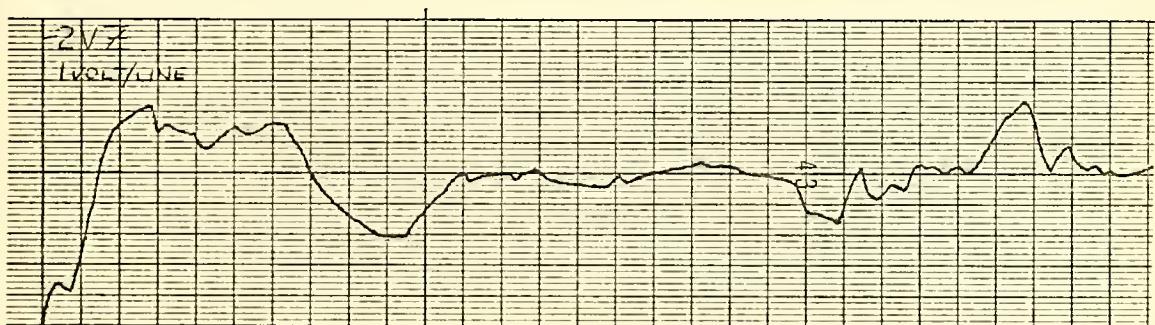
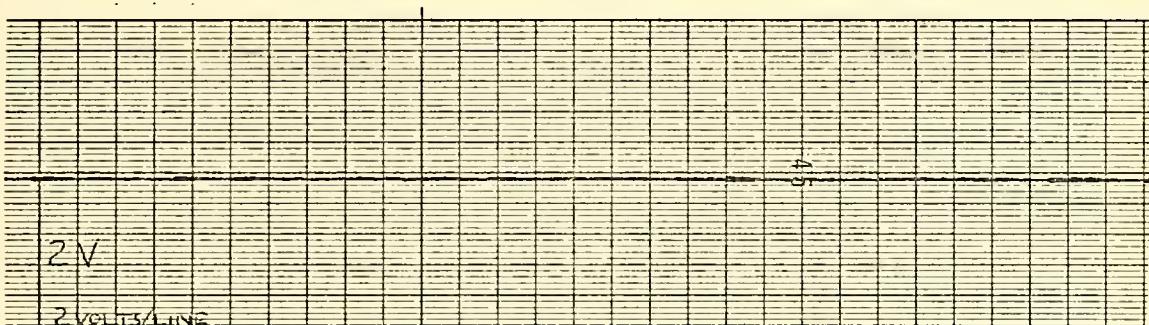
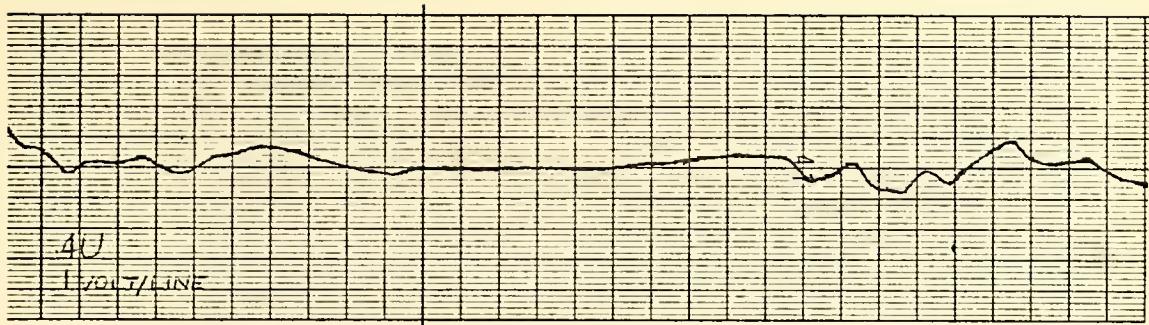
PILOT B, NORMAL



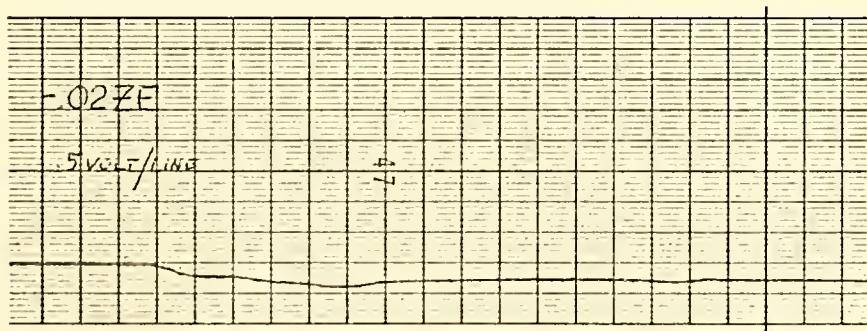
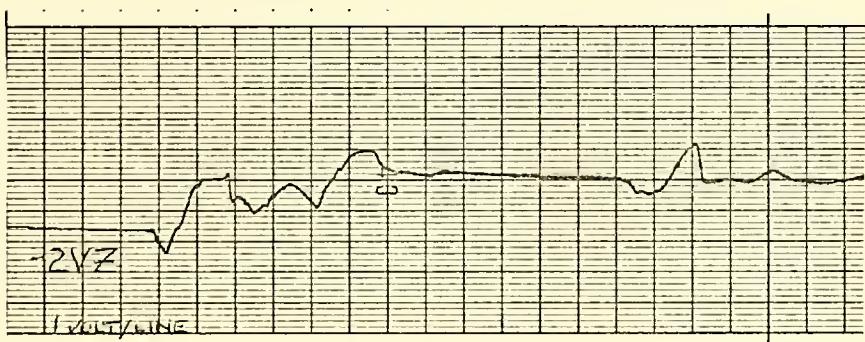
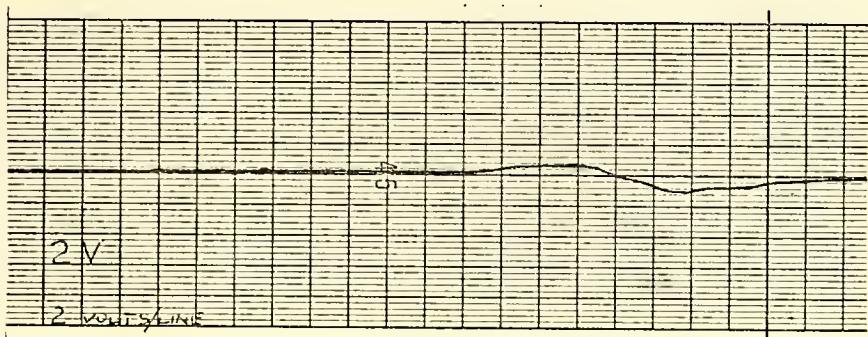
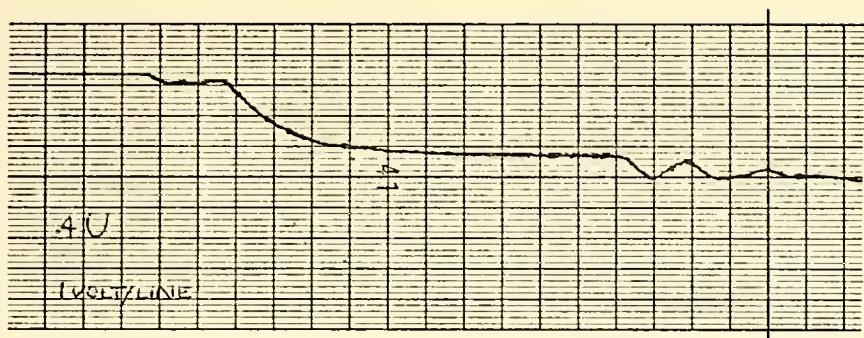
PILOT B, AUTOMATIC



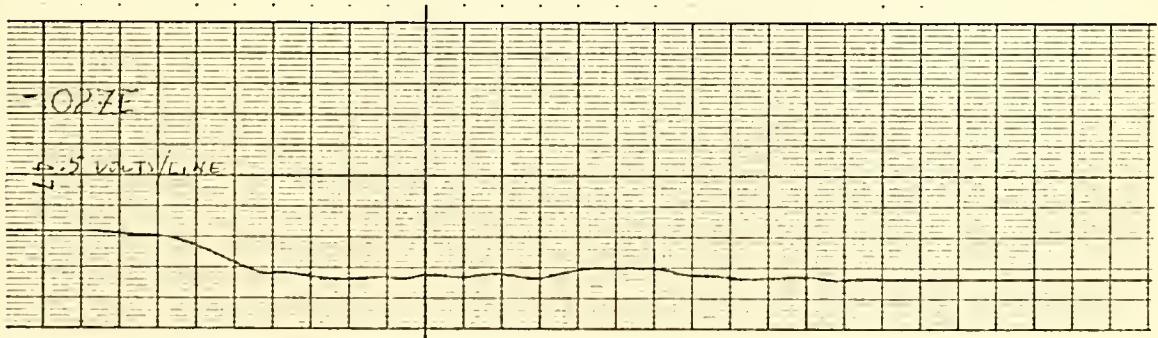
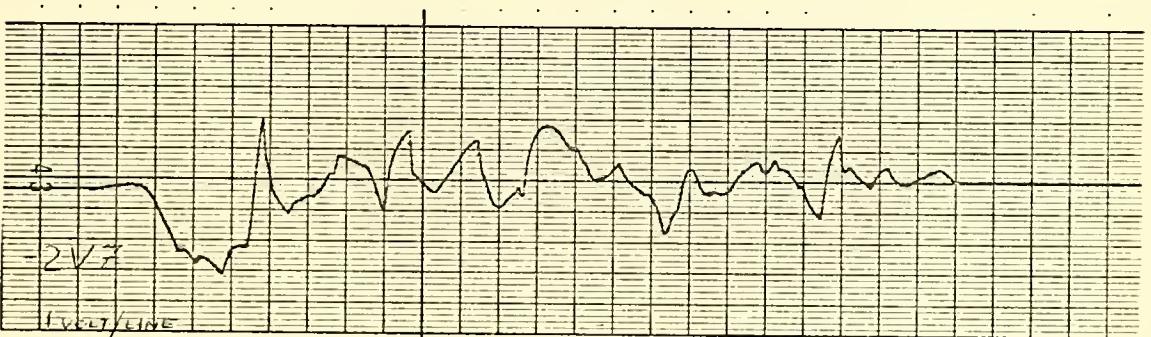
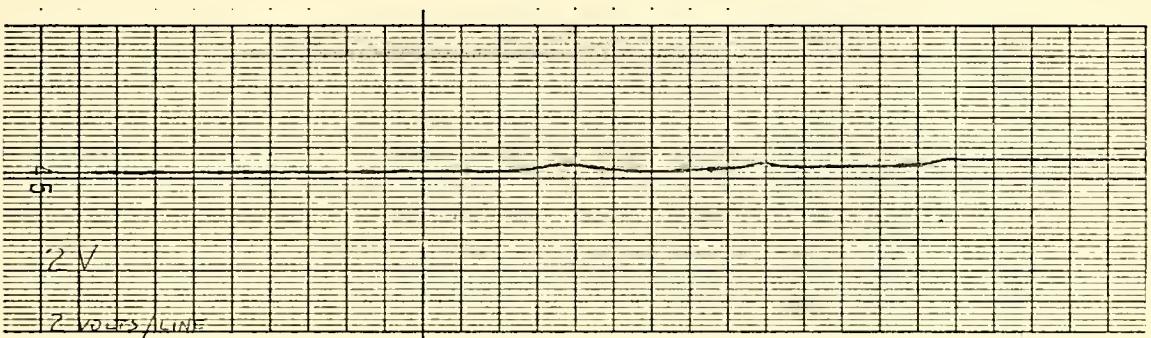
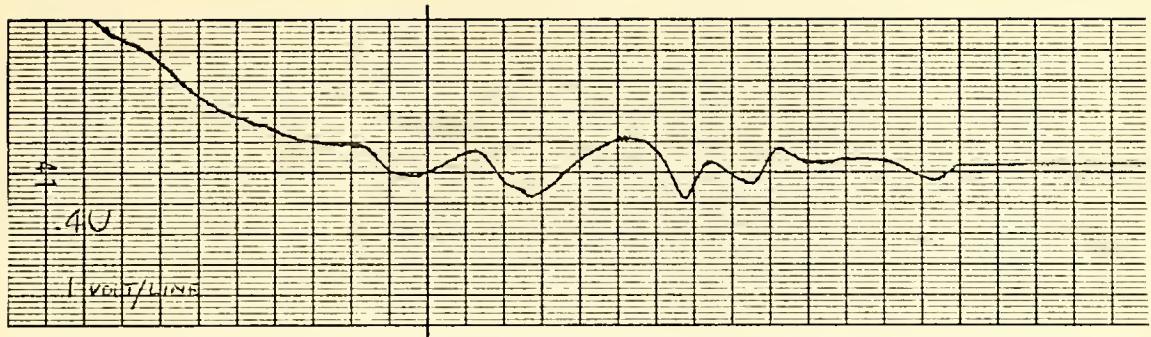
PILOT C, NORMAL



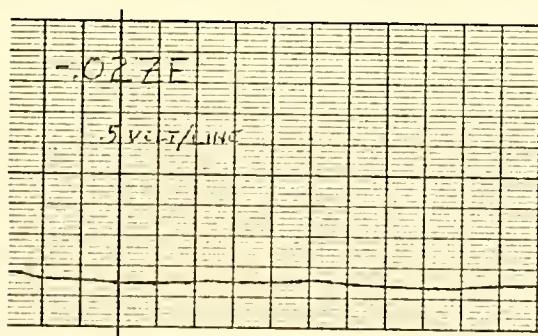
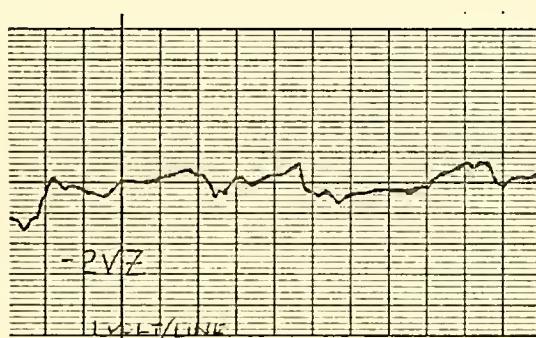
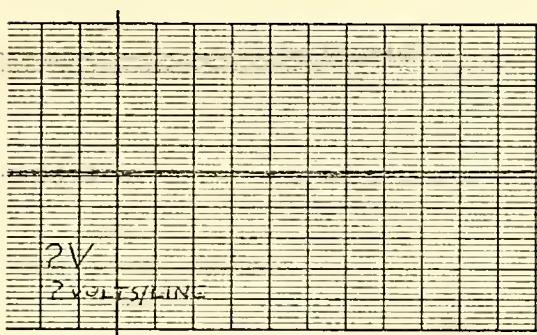
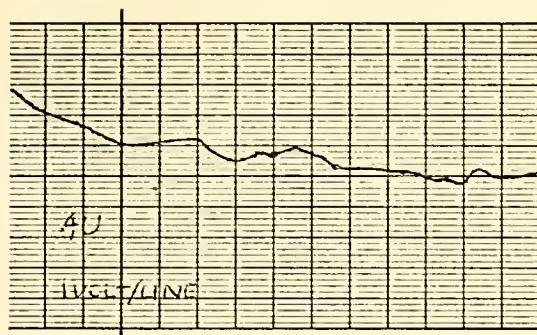
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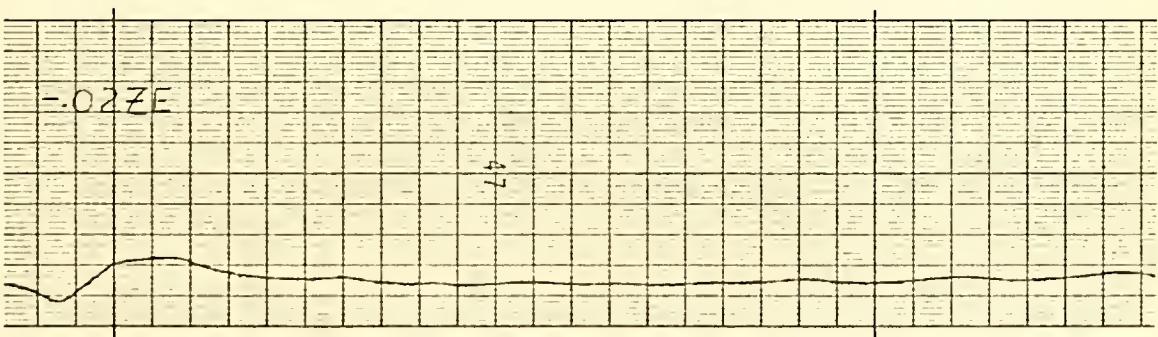
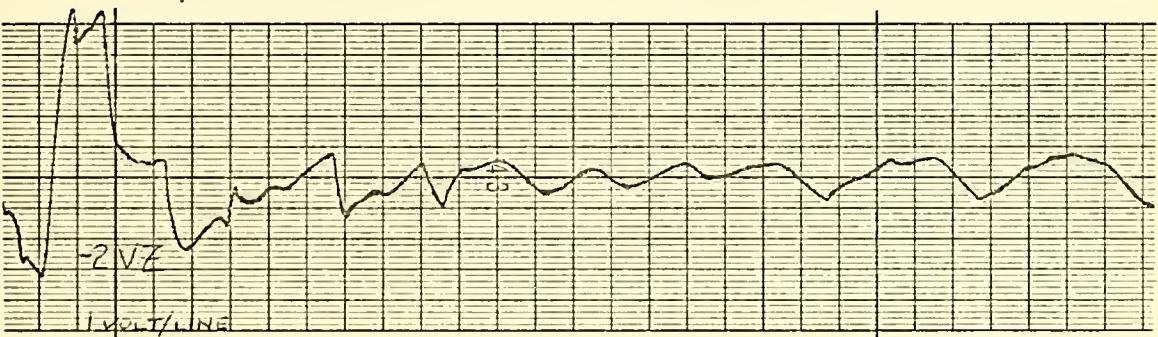
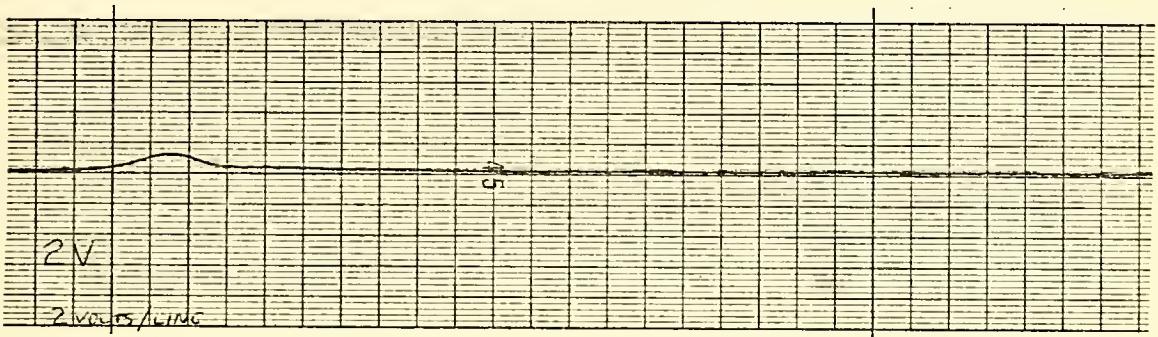
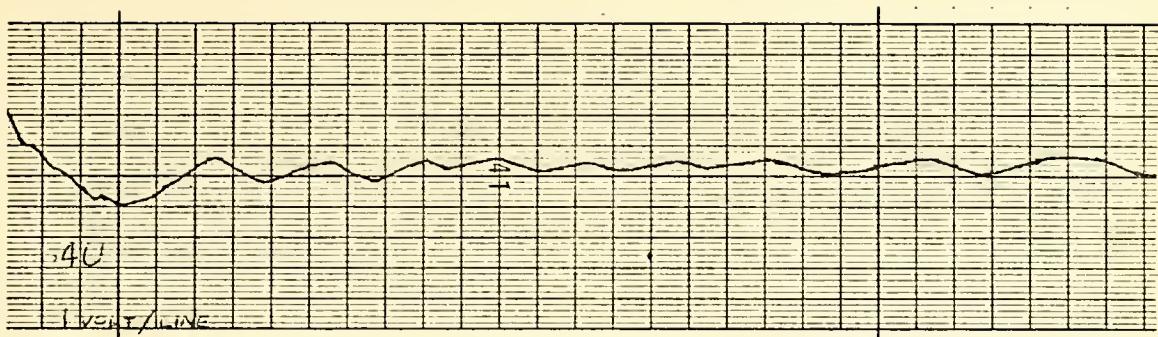
PILOT D, NORMAL



PILOT D, AUTOMATIC



PILOT E, NORMAL



PILOT E, AUTOMATIC

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